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THE GEOLOGY OF THE STONEWALL MOUNTAIN VOLCANIC CENTER, NYE COUNTY, NEVADA

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

Duncan Foley, B.A., M.Sc.

*****

The Ohio State University
1978

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"... in short a country in ruins dissolved by the peltings of the storms of the ages and turned inside out, upside down, by terrible convulsions in some former age."

P.P. Pratt, 1849
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Major Field: Paleovolcanology

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Studies in Isotope Geology. Dr. John F. Sutter

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CHAPTER 1

INTRODUCTION

Stonewall Mountain is in southwestern Nye County, Nevada, approximately 15 miles southeast of the town of Goldfield.

Stonewall Mountain covers about 100 square kilometers, and rises in elevation from 1430 meters (4700 feet) on the surrounding playa to a peak at 2520 meters (8275 feet). The topography is moderately rugged, with several valleys having more than 300 meters of relief. The climate is arid, with yucca, cholla, and beaver tail cactus, as well as sage and ephedra, composing the vegetation on the lower slopes. The upper slopes are locally covered by a pinon-juniper forest. Access to the base of the mountain is available by roads that locally are impassable to conventional vehicles. Deer and wild horse trails provide routes to the interior portions of Stonewall.

Regional Geologic Setting

Stonewall Mountain is in the western portion of the Basin and Range province, along the Walker Lane (Locke et al., 1940), and is adjacent to the southwestern Nevada volcanic field (Byers et al., 1976; Christiansen et al., 1977) (see Figure 1).

Cenozoic volcanism in the Basin and Range province has been
Figure 1. Location of the Stonewall Mountain Volcanic Center.
divided into an older episode of dominantly intermediate composition (Lipman et al., 1972) which, following the inception of extensional tectonics about 17 million years (m.y.) ago (Ekren et al., 1968; Stewart et al., 1977; Stewart, 1971; Noble, 1972), was succeeded by a younger episode of "fundamentally basaltic" volcanism, that also includes alkaline and peralkaline fields (Christiansen and Lipman, 1972). Alkaline chemistry and 5.8 m.y. to 8.4 m.y. dates from the rocks of Stonewall place in this mountain as part of the younger period of activity (see Chapters 3 and 4 on chemistry and K-Ar dating).

The most recent episode of tectonism in the Basin and Range province is characterized by development of mountain ranges that are bounded on at least one side by steeply-dipping normal faults (Stewart, 1971). Stonewall Mountain has such faults on its north and west sides.

The Walker Lane is a zone of right-lateral displacement by faulting and oroflexural folding (Nelson, 1965; Shawe, 1965; Albers, 1967), which may be tectonically related to similar offsets in the Death Valley area (Stewart, 1967; Stewart et al., 1968), and in the Las Vegas shear zone (Longwell, 1960). The current episode of offset along the Walker Lane began about 17 m.y. ago (Ekren et al., 1968). Geophysical studies (Greensfelder, 1965; Prodehl, 1970) indicate that the Walker Lane may be related to a zone of local crustal thickening. The observation that many volcanic centers are located along the Walker Lane (Orkild, in Ekren et al., 1971) is
further indication of its regionally significant nature. Stonewall Mountain is located near the Walker Lane, and, as data gathered during this research indicate, seems chronologically and chemically related to some of these other centers.

The southwestern Nevada volcanic field is also located along the Walker Lane. This field is an 11,000 square kilometer area composed of ash-flow tuffs, with source complexes that cover 1,800 square kilometers; volcanic activity took place from 16 to 6 m.y. ago (Christiansen et al., 1977). Stonewall Mountain is near the northwest edge of the volcanic field, about 35 kilometers from the nearest volcanic center within the field. Several ash-flow tuff units adjacent to Stonewall, however, have been traced to sources within the field.

Previous Geologic Investigations of Stonewall Mountain

Although Stonewall Mountain was first shown as an unnamed peak on a map accompanying the Wheeler Survey report of 1871, and mining was taking place in the adjacent Gold Point, Gold Mountain, and Montezuma districts during the 1860's (Paher, 1971), it was not until the turn of the century that the first report on the geology of Stonewall was published. J.E. Spurr (1903) recognized that the mountain is a volcanic center, and considered it "... so deeply eroded that it can not be of very recent age." Spurr believed rhyolites on Stonewall (now recognized as ash-flow tuffs) were older than other rhyolites in the region.
Ball (1906, 1907) investigated Stonewall as part of his regional studies of the geology in Nevada and California. He identified several sequences of rhyolite flows and quartz syenite and quartz monzonite porphyry intrusions. Ball also noted limestones and tuffaceous sediments, as well as quartz veins that locally contain gold.

Although only small amounts of gold and silver have been mined on Stonewall, the mountain has been mentioned in several compilations of Nevada mining districts (Heikes, 1912; Hill, 1912; Schrader et al., 1917; Weed, 1922; Lincoln, 1923; Hewett et al., 1936; Kral, 1951). Stonewall Mountain is also shown on several maps depicting mineral resources of Nevada (Bonham, 1967; Jerome and Cook, 1967; Schilling, 1969, Albers and Kleinhampel, 1970).

The geology of Stonewall Mountain has been described in several recent studies of volcanic and sedimentary rocks in western Nevada. Ekren (1968, p. 15) indicates, without discussion, that Stonewall is older than 11 m.y. Ekren et al. (1971) comment only on the area immediately east of Stonewall, where they identify several rhyolite hills and small basalt flows. Cornwall (1972) reported that the major portion of the mountain is composed of steeply-dipping welded tuffs that have been intruded by quartz latite. He also briefly discussed the non-volcanic Precambrian rocks, and the mining history. He concluded, on the basis of field relations, that Stonewall Mountain is older than both the major air-fall and water-worked tuff east of the main portion of the mountain, and the 7.5
m.y. Spearhead tuff. Stonewall Mountain is mentioned briefly in several other publications in the geologic literature (Noble et al., 1976; Rowen et al., 1974, 1977) and in the popular press (Strong, 1974).

Ashley (1974) summarized the knowledge of the geology of Stonewall Mountain prior to this study. He described Stonewall as a "... Tertiary volcanic center with its own volcanic section," and mentioned widespread tuffs, rhyolite and quartz latite flows and breccias, and intrusive rhyolites, trachytes, and latites. He agrees with Cornwall in assigning Stonewall an age older than the Spearhead tuff, but regards it as younger than the major air-fall and water-worked (Sibert ?) tuff. Late Precambrian and Paleozoic sedimentary rocks are mentioned, and he concludes by saying that other than the major fault along the north side of the range, the "... structural geology of the Stonewall Mountain volcanic center is poorly known."

Present Research

This study examines in detail the igneous rocks and structural geology of Stonewall Mountain in order to resolve several questions that previous researchers were unable to answer. These questions are:

1. What are the rock types of Stonewall Mountain? What is the areal distribution of individual units? How are the units related structurally and stratigraphically? Are the tuffs, flows, and intrusions related petrographically and chemically?

2. How old is Stonewall Mountain?
3. What is the geologic history of Stonewall Mountain? Is it a volcanic center, as has been suggested? If so, is Stonewall similar in rock type, rock chemistry, age, and historical development to other Tertiary volcanic centers in western Nevada?

The answers to these questions were sought through a program of field mapping, followed by petrographic, chemical, and isotopic studies. The field mapping was done during August and September, 1974, and August, September, and October, 1975 and 1976. Mapping on aerial photographs was transferred by stereo plotter to a 1:24,000 scale base map.

Representative samples of the rock units on the mountain were collected. Thin section study of these samples was accompanied by chemical and K-Ar analyses. Chemical analyses were done by XRF, flame photometer, and wet chemical methods. K-Ar analyses were done at Ohio State University under the direction of Dr. John F. Sutter, following the methods of Dalrymple and Lanphere (1969).
CHAPTER 2

FIELD CHARACTERISTICS AND LITHOLOGIES

OF THE ROCK UNITS ON STONEWALL MOUNTAIN

INTRODUCTION

The sedimentary, intrusive, and extrusive rocks of the Stonewall Mountain volcanic center exhibit much variation in their mode of occurrence and in their individual lithologies. The rocks are generally well exposed, although talus slopes, landslides, and alluvium prevent establishing firm conclusions about some structural and stratigraphic relationships.

Field and petrographic data for each unit mapped on Stonewall are reported here. The distribution of map units is given in Plate 1 (Appendix A), and cross sections of the volcanic center are depicted on Plate 2 (Appendix B). Place names are indicated on Figure 2.

The wide range of original lithologic variation within some units, and local secondary alteration, have in some cases made it difficult to determine specific affinities for individual outcrops. These intermediate rock types are especially common in the thick sequence of ash-flow tuffs that covers most of the mountain; small exposures of rocks with indeterminate affinities have been included in the dominant map unit of their outcrop area.
Figure 2. Index map of locations referred to in text.

N = Northumberland, T = Tonopah, MH = Monitor Hills, CR = Cactus Range, SP = Silver Peak, G = Goldfield, R = Ralston, BR = Belted Range, BM = Black Mountain, TM = Timber Mountain, I = Inyo Range, SM = Stonewall Mountain
PRE-TERTIARY ROCKS

Wyman and Reed Formations (Per and Pew)

The oldest rocks on Stonewall Mountain are interbedded siltstones and limestones (map unit Pew) which have been correlated by Cornwall (1972) with lithologically similar rocks of the Wyman Formation in Esmeralda County. Outcrops of the Wyman Formation are found only in the northwest corner of Stonewall.

The Wyman Formation on Stonewall Mountain is composed of gray, olive green, and brown siltstones and fine-grained sandstones, with interbedded gray carbonates. The clastic rocks typically show 1-10 mm. beds, with some soft-sediment deformation in the sandstones. The carbonates range from light gray to dark gray, and crop out in ledges 1-10 meters thick. Although fossils have been reported from the Wyman Formation in the Inyo Mountains (Wiggett, 1977), none were found in these strata on Stonewall. The siltstones have been metamorphosed to hornfels. Epidote occurs locally along fractures, and the Wyman Formation contains pyrite in the vicinity of the Yellow Tiger Mine on the northwest corner of the map area.

The base of the Wyman Formation is not exposed on Stonewall, however the upper 200 meters of the Wyman are preserved beneath the apparently conformable contact with the overlying Reed Formation.

The Reed Formation (map unit Per) is exposed along the northwest margin of Stonewall, where it forms conspicuous light-colored outcrops. Cornwall (1972) reported Stonewall Mountain as the only
occurrence of the Reed Formation in southern Nye County.

On Stonewall, the Reed Formation is composed of massive gray dolomite and thick-bedded yellow sandy dolomite. Differential weathering in some of the dolomite locally reveals laminae about 2 mm. thick; these beds in some places show cross-lamination. An isolated outcrop of ortho-quartzite is exposed along the southern margin of the outcrop of the Reed Formation, and may represent a distal portion of the Hines tongue (Nelson, 1962).

About 450 meters of Reed Formation are exposed above the Wyman; the top of the Reed is not preserved. Wiggett (1977) indicates that the base of the Cambrian is near the top of the Reed; thus the entire section preserved on Stonewall may be Precambrian.

The Wyman and Reed Formations have been deformed by at least one, and perhaps several, tectonic events during which the rocks have been folded into an apparent southwest-plunging syncline. Some small-scale folds in the Wyman are consistent with drag along the flanks of this syncline. Tectonic events may also be responsible for the low-grade metamorphism of the Wyman Formation, and the highly jointed nature of the rocks. The syncline was faulted prior to igneous activity, and locally the section has been repeated. Where faulted, the Reed Formation is commonly brecciated and stained orange-red. A 20-meter-thick breccia zone is preserved in the Reed where it has been cut by high-angle faulting along the west edge of the mountain.

The Wyman and Reed Formations are cut by black calcite and white calcite veins, which are as much as 3 meters thick. These veins
typically strike north-south and may represent hydrothermal activity related to the intrusion of an underlying monzonite.

Emigrant Formation (Ge)

Strata correlative with the Cambrian Emigrant Formation (map unit Ge) crop out along the northeast and southeast margins of Stonewall. The northern outcrop of the Emigrant Formation was correlated by Cornwall (1972) with exposures of the Wyman Formation in the Monitor Hills and the Belted Range in Nye County, but Stewart (pers. comm., 1975) believes that although no diagnostic fossils have been found on Stonewall, these strata are probably correlative with the upper limestone and chert member of the Emigrant Formation (Albers and Stewart, 1972).

The Emigrant Formation on Stonewall is composed of 2-8 centimeter thick beds of interlayered dark-red chert and gray limestone (Figure 5). Limestone in the southern outcrop is pale red-gray. The chert locally forms as much as 70 percent of the rock. One hundred and twenty meters of the unit are exposed in the northern outcrop; the total thickness is uncertain because neither the lower nor the upper contact is exposed.

The Emigrant Formation in one place is in apparent fault contact with the Eleana Formation described below; elsewhere it is surrounded by volcanic units.
Eleana Formation (Me)

A small exposure of conglomerate (map unit Me) with rounded quartzite cobbles and pebbles in a well-indurated medium-grained sandstone matrix, crops out adjacent to the northern outcrop of the Emigrant Formation. This unit is tentatively assigned to the Eleana Formation. A conglomerate facies of the Eleana Formation has been described by Ekren (in Cornwall, 1972) from the Cactus Range, about 25 kilometers northeast of Stonewall. Lack of similar facies in other units exposed in Esmeralda County or southern Nye County suggests that correlation of the unit on Stonewall with exposures in the Cactus Range is reasonable.

The outcrop on Stonewall is 3-6 meters wide by about 10 meters long. Bedding is poorly developed; minor sandstone lenses show cross-stratification that indicates that the outcrop is right side up.

Interpretation of Pre-Tertiary Units

Structurally, the pre-Tertiary rocks of Stonewall are preserved as large blocks floating on, and intruded by, the igneous rocks, in a manner generally similar to that reported by McKee (1974) for the Northumberland caldera, where blocks of Ordovician Vinnini Formation overlie Oligocene tuffs. The Precambrian and Paleozoic rocks on Stonewall were folded and faulted during pre-Tertiary orogenic events; evidence for tectonic activity in the area is provided by the quartzite conglomerate, which may be interpreted as clastic material shed from the Antler orogenic belt (Cornwall, 1972; Roberts, 1972). These rocks have been truncated by high-angle faults on both
the north and west sides of Stonewall.

INTRODUCTION TO TERTIARY UNITS

Tertiary rocks on Stonewall Mountain include rhyolites, dacites, andesites, air-fall tuffs, areally restricted volcanlastic sediments, minor basalt, and a thick sequence of ash-flow tuffs. Monzonite and anorthoclase-bearing monzonite intrude many of the volcanic units. Formal names have not been proposed for these igneous rock units.

It has not been possible to demonstrate, in all instances, that isolated outcrops of lithologically similar units are stratigraphically equivalent; however, for ease of discussion below, such outcrops have been combined. No fossils have been found in the Tertiary rocks on Stonewall, and correlation of rock units here with units in other areas has not been possible by different methods.

EARLY EXTRUSIVE UNITS

Andesite and Dacite (Ta and Td)

The oldest volcanic rocks on Stonewall are andesite flows and breccias (map unit Ta) and dacite flows (map unit Td), which are overlain by the rhyolite flow and breccia unit described later. These units are also in possible fault contact with several tuffs in the principal ash-flow tuff sequence (p. 24-43). The andesite has been sampled for chemical analysis (sample 58).

The andesite flows are aphanitic, and black to dark purple. Where brecciated, they contain sub-angular to well-rounded fragments
of andesite in an andesite matrix. Some of the andesite shows propylitic alteration. Outcrops of andesite are generally less than 10 meters on a side, although one is 400 m. long.

The andesites contain as much as 20 percent phenocrysts of plagioclase that typically range in size from 0.5 to 1 mm., are pervasively altered to calcite, and are sub-parallel. Pyroxene, amphibole, and olivine phenocrysts account for about 5 percent of the rock, are usually less than 1 mm. long, and have been altered to sericite, carbonate, and opaque minerals. The groundmass is composed of microlites of plagioclase, with a fine grained opaque dusting, and secondary carbonate and sericite. Sparse lithic fragments of quartzite are contained within the andesites. Calcite filled vesicles also occur in the andesites. Although the rock falls in the basalt field of Streckeisen's (1967) petrographic classification, it is chemically an andesite, and is therefore considered an andesite in this discussion.

The dacite has a dark purple groundmass and contains about 10 percent anhedral unaltered orthoclase phenocrysts, about 5 percent anhedral embayed quartz phenocrysts as much as 5 mm long, laths of altered plagioclase to lengths slightly greater than five mm., and ferromagnesium minerals that have been replaced by opaques. The groundmass is composed of sub-parallel microlites of plagioclase and altered mafic minerals with a fine grained opaque mineral present throughout. Sericite and calcite are common throughout plagioclase and mafic phenocrysts and in the groundmass.
Outcrops of andesite and dacite are typically highly jointed; several are truncated by low to high angle faults. The base of neither unit is exposed. The andesite has been brecciated by, and incorporated as xenoliths within, the overlying rhyolite (Figure 3). The contact between the andesite and the dacite is steep, and may be a fault.

Although only one outcrop of andesite is clearly overlain by and included as breccia fragments within the rhyolite, the general petrographic similarity of the andesites, and their exposure in apparently similar stratigraphic position, has led to their being grouped together.

Rhyolite (Tr<sub>1</sub>)

The andesites are overlain by rhyolite (map unit Tr<sub>1</sub>) which is characterized in the field by extensive alteration and many breccia zones. This rhyolite is exposed along the northern side of the mountain, south and east of Stonewall Spring (Stonewall Spring is the area identified as "Water Tank" and "Mill" at the center of the north edge of the mountain).

The primary criterion for the field identification of this rhyolite is the presence of quartz or feldspar phenocrysts in an aphanitic groundmass that shows, at least locally, flow banding. No regular pattern in the distribution of individual vitric, lithic-rich, flow-banded, or breccia zones within this rhyolite has been determined.
Figure 3. Andesite (Ta) that has been brecciated by, and incorporated within, the oldest rhyolite flow and breccia unit on Stonewall. The scale is seventeen centimeters long.
The vitric zones are discontinuous, and have spherulites in five millimeter thick, regular bands. These zones show some devitrification. Phenocrysts form less than 10 percent of this zone.

The lithic-rich zones contain xenoliths of quartzite and sparse volcanic rocks, in an altered groundmass.

Flow-banded rhyolite is interbedded with the other types of rhyolite within this unit, and forms many of the cognate blocks in the rhyolitic breccias. Typical flow-banded zones are less than two meters thick, and the flow banding is discontinuous within individual outcrops. Layers within the flow-banded rhyolite that contain five to 10 percent quartz and feldspar phenocrysts are intercalated with zones that contain less than five percent phenocrysts. Sparse outcrops of rhyolite that include pumice blocks have been found.

Breccia zones are especially common in the western portions of the outcrop area. The breccias form ledges, and have varied lithologies. Some are composed of angular to sub-angular fragments of volcanic rocks and quartzite, less than 1 cm across, in a red to red-orange aphanitic groundmass. The volcanic fragments are commonly flow-banded rhyolite, which in some places shows reaction rims with the surrounding aphanitic matrix. Other breccias have larger fragments, typically of either flow-banded or quartz-rich rhyolite, but rarely of mafic rocks. Some ledges of these breccias have rounded boulders of rhyolite in a rhyolite matrix (Figure 4). It has not been possible to correlate breccia zones between adjacent outcrops.

All of these units show argillic or propylitic alteration, or
Figure 4. Rounded boulder of rhyolite in a rhyolitic matrix, from map unit $T_{r_1}$.
bleaching, to some degree. In some outcrops the rocks are nearly fresh, but in most the feldspars and groundmass are altered, and quartz is the only unaltered phenocryst. Liesegang rings and iron-oxide staining along fractures are associated in some places with the bleached rocks. No pattern for distribution of the alteration zones is apparent.

Phenocrysts of quartz, sanidine, and sparse mafics are found in the rhyolites. Quartz phenocrysts are anhedral, deeply embayed, and as much as 2 mm. across. Sanidine is the dominant feldspar, and is subhedral to anhedral and typically less than one-half mm. long. In some thin sections, both twinned and zoned plagioclase phenocrysts are present. These phenocrysts average one to 1.5 mm., are subhedral, and locally are unaltered. In only one section of the rhyolites were biotite and amphibole (?) present; these minerals have been replaced by iron ores and sericite.

Quartz occurs in the groundmass as anhedral single grains, less than 0.15 mm. in diameter and as aggregates of crystals that appear to be secondary, and to fill voids and replace vitric areas. The groundmass of the flow rocks is composed of a fine-grained dusting of iron ores, microlites of quartz and feldspar that show no preferred orientation direction, and sericite. The vitric zones contain spherulites as much as 3 mm. in diameter.

The rhyolites have been intruded by quartz and carbonate veins that range in width from microscopic to more than a meter. The quartz veins show offset in both outcrop and thin section.
Flow banding in the rhyolites is generally moderately to steeply dipping. The direction of dip is typically north, away from the main part of Stonewall Mountain.

The rhyolites have been cut by high-angle faults, the displacements of which are too small to depict on Plate 1 or 2. Joints are common in the rhyolites, and many have slickensides. Some of the breccia zones in the rhyolite are apparently parallel to the high angle fault along the north side of the mountain.

The rhyolite, at least in part, overlies the andesite and dacite already described. A dike of rhyolite has intruded, but apparently not altered, the limestone and chert of the Emigrant Formation (Figure 5). The rhyolite also occurs along the margins of the Emigrant strata; here also contact effects have not been observed.

The rhyolites are overlain by, and may be in fault contact with, several units of the thick ash-flow tuff sequence (p. 24-43) that forms most of the mountain. These contacts are typically sharp, and range from nearly horizontal to steeply dipping.

The rhyolites have been intruded by monzonite along the northern side of the mountain. Where the rhyolite is in contact with fine-grained marginal phases of the monzonite, the contact is difficult to discern.

East of the Emigrant Formation outcrops, the rhyolite is overlain by a thick landslide deposit.
Figure 5. Contact between the Emigrant Formation (Ce) and a rhyolite dike (Tr1). Arrows indicate the contact. Seated figure on left side of photograph indicates scale.
Interpretation of the Rhyolite (Tr₁)

Outcrops showing large rounded boulders of rhyolite in a rhyolite matrix in some of the breccia ledges suggests that these outcrops are close to, if not within, the rhyolite vents. Rhyolite flows and domes typically brecciate the surrounding rock units as they are forceably emplaced (Bohmer, 1965). Inclusions of quartzite, andesite, and other volcanic fragments in the rhyolite suggest that it was emplaced through and upon these rocks. The quartzite may be from the Eleana Formation or the Hines Tongue of the Reed Formation, which were discussed earlier, or it may be from pre-Tertiary units not exposed at the surface. The andesite was discussed previously, and the other volcanic fragments may be from units, such as tuffs from the Timber Mountain volcanic center, that are exposed near Stonewall (Byers et al., 1976).

Inception of igneous activity with emplacement of rhyolites has been described by Lipman (1975) from the Cat Creek volcano in Colorado; such rocks may represent tapping of the upper portion of the differentiated, but still rising, magma. This rhyolite was emplaced adjacent to the high-angle fault along the north side of Stonewall; this fault may have served as a zone of weakness along which the magma rose. The older andesites and dacites may represent the tapping of the magma at a deeper level, or they may be from a second, more mafic magma.
Volcaniclastic Sandstones (Ts)

Volcaniclastic sandstone beds, (map unit Ts) which show local propylitic alteration, are intercalated with both rhyolite flows and breccias (Tr₁), along the north side of the mountain. Beds within these sandstones average two to five centimeters thick, and are composed primarily of rhyolite fragments, with andesite, quartzite, and shale also present. Grains of quartz, potassium feldspar and plagioclase have locally been replaced by calcite or sparse opaque minerals. The matrix of the sandstone is quartz, feldspar, and sericite.

Contracts between the volcaniclastic sandstone and the rhyolite flow and breccia unit are not clearly exposed. In some outcrops, bedding in the sediments is apparently truncated by the rhyolites, which suggests that the contact is a fault. In other areas, the sediments apparently overlie the rhyolites.

THE ASH-FLOW TUFF SEQUENCE

A sequence of ash-flower tuffs with minor intercalated lava flows dominates the volcanic section on Stonewall. These tuffs form most of the high ridges of the mountain. The tuffs and flows have been separated into: a unit of trachytic tuff (Ttt) with few lithic fragments and phenocrysts and dominant in the western part of Stonewall; a unit of rhyolitic breccia (Trb) locally preserved stratigraphically above the trachytic tuff; a unit of phenocryst- and lithic-rich tuff (Tpl) that is preserved in isolated outcrops.
along the northern portion of the mountain, as well as in massive outcrops in the western part of Stonewall where it is intercalated with a rhyolite flow and volcaniclastic sedimentary unit (Tms); and a unit of lithic-rich tuff (Trlt) that dominates the highest ridges of Stonewall and has correlative units extending to the southwest and southeast margins of Stonewall. Because it was not always possible to assign individual outcrops to a particular tuff unit, limited exposures of several tuffs may be present within areas mapped as a single unit.

The typical zones of ash-flow tuffs (Smith, 1960a, 1960b; Ross and Smith, 1961) are only rarely developed in the Stonewall tuffs, and therefore individual ash-flow units are difficult to identify. The tuffs have been disturbed by faulting and minor folding. It is likely that many small faults exist in the tuffs, but cannot be recognized because of the uniform character of the rocks, and the lack of welding and crystallization zones. Densely welded zones are typically the only zones preserved on Stonewall Mountain. Unwelded and partially welded zones that might indicate breaks in the cooling history, and vitrophyres that might indicate the basal portion of individual ash-flow units are rare. Devitrification and granophyric crystallization are present; vapor phase crystallization and fumerolic alteration are uncommon in the tuffs on Stonewall Mountain.
Trachytic Tuff (Ttt)

A densely welded, dark-gray ash-flow tuff is exposed along the northern and western portions of the mountain (map unit Ttt). The rock is a trachyte in the classification of Streckeisen (1967), and thus the term trachytic as applied to this unit refers only to rock composition, and does not have textural implications.

The trachytic tuff does not display the typical zonation of a welded tuff; only the crystallized zone is preserved. Vitrophyres that can be definitely related to the tuff have not been identified, and zones without intense compaction are rare. Several breccias have noted within the trachytic tuff. These breccias typically are composed of angular blocks of tuff in a fine-grained matrix. The trachytic tuff, especially near the monzonite intrusion, is cut by veins of quartz and black and white calcite, which locally are as much as four meters thick. The tuff commonly shows iron-oxide stains adjacent to the veins.

Phenocrysts form from two to ten percent of the total volume of the tuff. Sanidine is the only common phenocryst phase, and is subhedral to anhedral, fractured, and typically 0.5 to 1.5 mm. across. In some phenocrysts, sericitic alteration is confined to cleavage surfaces, in other phenocrysts the entire mineral has been replaced. Embayed quartz phenocrysts, as much as 2 mm. across, and amphibole (?) phenocrysts now altered to hematite are rare in this unit.
The groundmass consists of randomly oriented submicroscopic quartz (?) and feldspar (?), sparse secondary biotite flakes, and magnetite. The tuff is characterized by devitrified glass shards and collapsed pumice that range in length from less than one millimeter to about five centimeters, and typically have a length to width ratio of about 20:1. The shards and pumice are deformed around phenocrysts. Devitirification of these has produced axiolitic growths of cristobalite (?) and feldspar on the edge of the shards with quartz and sanidine crystallization at the center.

Quartzite, siltstone, and volcanic fragments are present in trace amounts in the trachytic tuff.

The trachytic tuff is exposed as individual blocks that range from 10 to more than 100 meters on a side. Contacts between blocks of tuff, where identifiable, are generally steep. Eutaxitic structures within the blocks are generally steeply dipping, and orientations vary from one block to another.

The trachytic tuff exhibits small scale faulting and folding (Figure 6), and several large faults (Plate 1) were identified in the field. Absence of marker beds in the tuff makes it impossible to accurately establish displacement along these faults. Movement on most of the smaller faults is probably less than one meter, whereas movement on the larger faults may be several tens of meters or more. A two to five centimeter spacing of joints is common in this tuff; in many places these joints have slickensides.
Figure 6. Small scale folds in the trachytic tuff. The hammer is 33 centimeters long.
The trachytic tuff disconformably overlies and is in fault contact with Precambrian rocks and with the older andesite (Ta; p. 14) and rhyolite flow and breccia units (Tr₁; p. 16). Along the western exposure of the tuff, it is in contact with a younger rhyolite breccia (Trb; p. 30). Ashley (pers. comm., 1975) suggested on the basis of the irregular attitudes of the contact, the lack of preservation of zones in the tuff, and the inclusion of fragments of trachytic tuff within the younger rhyolite, that this rhyolite breccia is most likely in intrusive contact with the trachytic tuff. In one area, the contact of this younger rhyolite with the trachytic tuff has been faulted. A phenocryst- and lithic-rich tuff (Tpl; p. 32), which overlies the rhyolite, also directly overlies the trachytic tuff along a poorly exposed contact; locally, a steeply dipping fault breccia is exposed along the contact of the trachytic tuff and the phenocryst- and lithic-rich tuff.

The trachytic tuff is both conformably overlain by, unconformably overlain by, and in fault contact with the thick red lithic tuff unit (Tr₁lt; p. 40) described below. Conformable relations between the trachytic tuff and the red lithic tuff are suggested in several areas by parallel orientations of eutaxitic structures, even though basal unwelded and vitrophyric zones are not preserved in the overlying red lithic tuff. In some areas, unconformable relations between the trachytic and red lithic tuffs are suggested by angular discordance between compaction directions for each unit. In many areas, however
the contact between the red lithic tuff and the trachytic tuff is marked by high angle faults that may have as much as 200 meters of displacement. Exact determination of displacement along these faults is precluded by the lack of distinct stratigraphic horizons within either unit.

Both the monzonite (Tm) along the northern part of the mountain, and the anorthoclase-bearing monzonite (Tms₁; Tms₂) along the central and southern parts of Stonewall, intrude the trachytic tuff. The intrusive nature of these contacts is shown by their steepness, the truncation of eutaxitic compaction directions by the monzonites, the absence of fault breccias, and the rare inclusion of fragments of tuff within the monzonites.

Rhyolite Breccia (Trb)

The trachytic tuff (Ttt) is locally in contact with a poorly exposed rhyolite breccia and lava and ash flow unit (map unit Trb) in the northwestern part of Stonewall. A possibly correlative outcrop of rhyolite is exposed along strike with this unit, at the western edge of the mountain.

The rhyolite is composed of a lower breccia overlain by a vitrophyre and then a flow-banded zone. The lower breccia contains angular to subangular blocks of rhyolite and trachytic tuff (Ttt) in a rhyolite matrix. Specular hematite occurs in one outcrop of the breccia. The black vitrophyre is locally one meter thick; it is not uniformly preserved throughout the unit. The overlying flow-banded zone varies from about 10 to 30 meters thick; locally shard textures are exhibited.
The rhyolite contains phenocrysts of sanidine, quartz, and plagioclase, but these account for less than five percent of the volume of the unit. The subhedral to euhedral sanidine phenocrysts are 0.2 to 2.0 mm. long, are rounded and fractured, and have largely been replaced by sericite and chlorite. Unaltered quartz phenocrysts are fractured, slightly embayed, and are less than 0.5 mm. in average length. Plagioclase is present as 1.5 mm. subhedral phenocrysts, nearly totally replaced by sericite. Sanidine forms more than 80 percent of the phenocrysts. In one sample, the sanidine phenocrysts are more heavily altered than the adjacent groundmass, and several have quartz stringers that do not continue into the groundmass; this suggests that some of the sanidine in this unit may be xenocrysts. The only lithic fragment seen in thin section was a rounded fragment of the trachytic tuff, one centimeter in diameter.

The groundmass of the rhyolitic rocks of this unit is vitric. A sample from an outcrop adjacent to the trachytic tuff unit has 0.05 mm. thick flow bands that contain cristobalite (?) and feldspar formed during devitrification. Sub-parallel, 0.5 to 1.5 mm. long shards, which show moderate compaction, and secondary alteration by the presence of chlorite, occur in one sample. The shards and flow banding are distorted around the phenocrysts and lithic fragments.

Attitudes in this unit (Trb) are difficult to obtain, however, the few measurable orientations suggest it dips steeply toward the northwest, and strikes in a southwest-northeast direction.
The rhyolite (Trb) is in fault contact with, and has intruded the trachytic tuff (Ttt). Fragments of rhyolite breccia are included in a matrix of the overlying phenocryst- and lithic-rich tuff (Tpl), the number of rhyolite inclusions decreases away from the Trb-Tpl contact.

Phenocryst- and Lithic-Rich Tuff (Tpl)

A phenocryst- and lithic-rich tuff crops out in the north and northwest portions of the mountain (map unit Tpl). Phenocrysts of feldspar, quartz, and minor mafics, and lithic fragments of quartzite, tuff, and sparse andesite are contained in a blue-gray tuffaceous groundmass. Welded zones typical of ash-flow tuffs are not present in this unit. Relict eutaxitic structures, however, are present, though rare; where preserved, they reach one centimeter in length.

The tuff (Tpl) is apparently more crystalline in its eastern outcrops, and more highly altered in its western outcrops. The tuff ranges from 10 meters thick in its eastern outcrop to more than 200 meters thick in its western outcrops (assuming no repetition or omission of parts of the tuff by faulting). Several high angle faults may be present but lack of marker beds prevented positive identification. Joints in the western portion of the tuff typically are spaced at 10 meter intervals, and propylitic alteration has occurred along some joints. The unit is cut by quartz and carbonate veins along its western exposures.

Phenocrysts compose 30 to 40 percent of the tuff. Orthoclase forms 70 percent of these, and is euhedral to subhedral, 1 to 3 mm.
long, and extensively replaced by sericite (?) along cleavage directions. Sanidine and quartz each account for about 10 percent of the phenocrysts. The sanidine is typically 0.5 mm. long, subhedral, and has an optically continuous overgrowth of potassium feldspar. The quartz forms broken, slightly rounded phenocrysts that average about 0.5 mm. in length. Subhedral broken phenocrysts of plagioclase (oligoclase?), which in some samples have been totally replaced by carbonate and sericite, form about 5 percent of the phenocrysts in the rock. Biotite, in flakes as much as 0.5 mm. which have reaction rims formed of blocky opaque minerals, and rare relict pyroxene, which is totally replaced by opaque minerals, also compose about 5 percent of the phenocrysts. Quartzite, andesite, trachyitic tuff, and flow-banded rhyolite are found as 0.5 to 5 mm. lithic fragments. Figure 7 is a photomicrograph of this unit. The groundmass of this unit contains shards which have devitrified to feldspar and cristobalite; sericitic alteration is common. Sparse spherulites, with diameters to 0.2 mm., are present. Feldspar, quartz, and opaques, as well as chlorite, epidote, and sericite, are in the groundmass. Multiple filling of fractures by quartz is shown in some sections. In Streckeisen's (1967) classification this rock is a quartz trachyte.

The phenocryst- and lithic-rich tuff (Tpl) is in fault contact with the Wyman Formation, and is exposed along the southern margin of the outcrops of the Eleana and Emigrant Formations. It is locally in fault contact with the trachyitic tuff (Ttt; p. 26) and the rhyolite
Figure 7. Photomicrograph of the phenocryst- and lithic-rich tuff. Q, quartzite lithic; s, altered sanidine phenocrysts, in a shard rich groundmass. Plain light; the field of view is approximately 3.4 by 2.2 mm.
breccia (Trb). It (Tpl) has been intruded by monzonite (Tm) along the northern edge of the mountain. The phenocryst and lithic-rich tuff is apparently intercalated with an isolated rhyolite (Tmr) described below, and lower units of the red lithic tuff (Trlt) that forms the bulk of the mountain. Stratigraphic relations between the isolated rhyolite (Tmr), a massive andesite, and this phenocryst- and lithic-rich tuff are discussed later, in conjunction with the andesite (Tad, p. 61).

Rhyolite (Tmr)

Several outcrops of flow-banded rhyolite and intercalated volcaniclastic sedimentary rocks (Tmr) occur adjacent to the monzonite (Tm) along the north side of the mountain, next to the massive andesite (Tad), and partially in contact with the phenocryst- and lithic-rich tuff (Tpl). The volcaniclastic sedimentary rocks show small-scale scour and cross-stratification which indicate they are right side up. The outcrops are discontinuous along the margin of the andesite. It has not been possible to correlate the rhyolite (Tmr) with any other rhyolites on the mountain. The rhyolite is composed of 0.1 to 1.0 mm. grains of quartz that are subhedral to anhedral and occasionally embayed, and euhedral sanidine as much as 2.0 mm. long, in an aphanitic, locally chlorite-rich groundmass. Incorporated in the rhyolite are angular fragments of the sedimentary rock of this map unit, of spherulitic rhyolite, of rounded quartzite, and a well rounded ash-flow tuff fragment. The ash-flow tuff fragment can not be correlated with any units on
Stonewall. Epidote has formed along phenocrysts and fractures in the groundmass of part of this unit. Zircon is present as accessory mineral.

Monzonite apparently intrudes the rhyolite (Tmr). The rhyolite and sedimentary rocks (Tmr) may be older than, intercalated with, or younger than and faulted against, the phenocryst- and lithic-rich tuff (Tpl). This rhyolite has tentatively been correlated with an inclusion, more than 5 m. in diameter, in the massive andesite (Tad).

Ash-flow and Air-fall Tuffs (Twt)

A sequence of unwelded to densely welded ash-flow and air-flow tuffs, with intercalated volcanioclastic sandstones, is found in the southeastern portion of the mountain (map unit Twt). These tuffs extend south of the mapped area, along a prominent mesa. K-Ar ages have been obtained for two samples from this unit (samples 38 and 65) and one sample (38) has been analyzed chemically.

The lowest exposed member of this unit is composed of well stratified tuffs and volcanioclastic sedimentary rocks in 0.5 to 20 cm. thick, lithic-rich beds. This member is overlain by an ash-flow tuff with eutaxitic texture and spherulitic devitrification in the groundmass. This ash-flow tuff grades upward into an overlying zone of crystal tuff, which is more than 30 meters thick. An air-fall tuff and a volcanioclastic sedimentary unit are locally exposed along the top of the crystal tuff. The air-fall tuff is composed of 0.5 to 1 cm. thick beds that alternate from coarse grained to fine grained. Where the air-fall tuff is not preserved, the crystal tuff is capped by a black, vesicular ash-flow tuff that forms
rubble on the top of the mesa south of Stonewall.

Coarse grained beds in the volcaniclastic sedimentary unit are composed of 0.5 to 1.5 mm. grains of sanidine, slightly altered biotite, zircon, and rare lithic fragments from a vitric tuff, in a dark red matrix with patches of sericite and accessory rutile. Fine grained beds in this subunit have 0.1 to 0.2 mm. grains of sanidine, and 0.1 to 0.3 mm. phenocrysts of biotite, in a feldspar, quartz (?), and sericite matrix. Sand-sized grains compose 45 percent of the coarse beds, and 10 to 40 percent of the fine beds; in both sanidine accounts for about 90 percent of the grains.

The ash-flow tuff that overlies the volcaniclastic sedimentary unit has about 20 percent phenocrysts. Sanidine accounts for 80 percent of the phenocrysts in the rock, and is present as subhedral to euhedral, fractured phenocrysts, which range in size from 0.3 to 3.0 mm. with an average length of 1.25 mm. Euhedral plagioclase, typically about 2 mm. long, but rarely as large as one cm., accounts for about 15 percent of the phenocrysts. Clinopyroxene and sparse biotite flakes, which have been replaced by sericite and opaque minerals, are the only other major phenocrysts present. The red aphanitic groundmass includes many devitrified shards that have been altered to sericite and carbonate veinlets which typically are less than 0.1 mm. wide.

The crystal tuff that overlies the volcaniclastic sedimentary subunit is cut by several small high angle faults that have brecciated the rocks and served as channels for fluids that
precipitated quartz and calcite veins. Dips of the eutaxitic structures in this unit, although locally high, are generally less than the dips in the welded tuffs (Ttt and Trlt) in the main part of Stonewall. The crystal tuff has widely spaced joints, many of which have slickensides. The crystal tuff forms debris as large as 10 meters on a side. These blocks are especially prevalent along the south margin of the map area. This tuff overlies an outcrop of the Emigrant Formation, and is in uncertain stratigraphic relationship with a rhyolite along the southeast margin of the map area. This tuff is in fault contact with an air-fall and water-worked tuff and with the thick red lithic tuff that caps the mountain. A breccia is locally exposed where the ash-flow tuff has been intruded by the less siliceous phase of the anorthoclase-bearing monzonite. Where the more siliceous phase of the anorthoclase-bearing monzonite has intruded this tuff, no breccia is developed.

**Tuffs - Southwestern Corner (Tts)**

A unit of ash-flow tuff, lava, and tuffaceous sandstones is exposed along the southwestern edge of the mountain (map unit Tts). This unit is characterized by sequences of ash-flow tuffs and lava flows overlain by breccia units and volcaniclastic sediments. In one outcrop, unbedded air-fall tuff is capped by bedded tuff, which in turn is overlain by a vitrophyre and a crystallized ash-flow tuff, in a sequence typical of an ash-flow tuff cooling unit (Smith, 1960a). The ash-flow tuffs of this unit (Tts) lack xenoliths. The intercalated
tuffaceous sandstones are lenticular, and range from 0 to 10 meters thick. Joints throughout this unit are commonly filled by small quartz veins; other alteration is not common.

Phenocrysts form about 25 percent of the ash-flow tuffs and lava flows. Of these, two-thirds are euhedral to anhedral broken resorbed sanidine phenocrysts as much as 3 mm. long. The sanidine is present as both individual grains and as glomeroporhps that are more than 4 mm. long. Twinned and zoned plagioclase is present as glomeroporhps to 3 mm., and sparse biotite and pyroxene that have been altered to opaque minerals are the other phenocrysts. The groundmass is iron-oxide stained and opaque. Flow textures are rarely identifiable, and are slightly more common than compressed shards. According to the classification of Streckeisen (1967), this rock is a latite.

The intercalated volcaniclastic sediments are composed of broken sanidine grains, 1 to 3 mm. long, and broken plagioclase laths as much as 2.5 mm. long. The matrix of the sediments is composed of sanidine grains, with biotite and sparse pyroxene that have been replaced by hematite and magnetite, sparse quartz, and a fine-grained opaque dusting. The larger grains are fractured, and show development of microbreccias. The fine-grained sandstones occur in 1 to 10 mm. thick beds, and are composed of angular to subrounded, 0.25 to 0.5 mm. grains of quartz and sanidina, in a sericitized groundmass.
Several small faults cut the tuffs. The crystal tuff is strongly jointed. Eutaxitic structures dip steeply near the contact between this unit (Tts) and anorthoclase-bearing syenite (Tms$_3$; p. 52); the dips decrease away from the contact.

The exact contact between this unit (Tts) and the anorthoclase-bearing syenite (Tms$_3$) is difficult to identify in the field. It has been located on the basis of a slightly finer groundmass texture in the tuffs and flows. The contact between this unit and a latite breccia unit (Tbs) is faulted.

**Red Lithic-Rich Tuff (Trlt)**

A light to dark red, often lithic-rich ash-flow tuff unit (map unit Trlt) dominates most of the mountain. Several vitrophyres crop out near the base of, and within, the tuff. These vitrophyres are typically less than 4 m. thick, discontinuous, and contain feldspar phenocrysts as well as volcanic and quartzite xenoliths. One vitrophyre shows folding (Figure 8). Unwelded zones in this tuff are found away from the central portion of the mountain. These zones are typically less than 3 m. thick, laterally discontinuous, and grade vertically into more typical crystallized tuff. Thus, although individual ashflows are difficult to identify, the unit as a whole probably consists of many separate eruptive units.

Breccias are common throughout this unit. Some, with angular fragments of tuff in an iron-stained matrix, can not be related to stratigraphic horizons and appear to be tectonic. Others, with tuff in a tuffaceous matrix, appear to be depositional. Veins are
Figure 8. Vitrophyre that shows folding along the base of the red lithic tuff. The dashed line depicts the approximate top of the vitrophyre.
rare; the largest is several meters thick and continues for several hundred meters.

This tuff varies greatly in thickness. Along the north edge of Stonewall, it is less than 10 meters thick, whereas as much as 500 m. of section is exposed along cliffs in the south-central part of Stonewall.

Phenocrysts form about 15 percent of the rock. Eighty-five percent of the phenocrysts are sanidine, which occurs as 0.5 to 3 mm. fractured grains that have sericitic alteration. Anhedral embayed quartz phenocrysts are typically smaller than the sanidine, and form about 5 percent of the phenocrysts. In some thin sections, no quartz phenocrysts were found. Plagioclase accounts for less than 2 percent of the phenocrysts; it shows extensive sericitic alteration. Biotite, although present in some sections as phenocrysts several mm. long, is rare in most of the tuff. It is typically altered to opaque minerals. Pyroxene (?) has been replaced by opaque minerals; these altered phenocrysts form about one percent of the phenocrysts in the unit.

In lithic-rich zones of the tuff, xenoliths form as much as 15 percent of the rock. The fragments are typically subangular to rounded, and no more than one cm. in diameter. Fragments of orthoquartzite, andesite (map unit Ta), rhyolite (map unit Tr1), and ash-flow tuffs (map units Ttt and Tpl), as well as volcanic units that can not be correlated with any units on Stonewall, have been identified within the lithic-rich zones of this tuff.
The groundmass of the tuff is characteristically red and shard rich. The shards are commonly less than 1 mm., and are devitrified to cristabolite and feldspar. Zeolitic spherulites are developed on the margins of some shards, with anhedral quartz and feldspar crystallized in the center of the shards.

On the basis of phenocryst composition, the rock plots near the field of trachytes (Streckeisen, 1967), but chemically, it is a dacite (Irvine and Baragar, 1971; see chapter 3 on chemistry).

Compaction directions on eutaxitic structures in the red lithic tuff generally have a steep dip. This, combined with complex relations between many adjacent attitudes suggests that the red lithic tuff, like the trachytic tuff (Ttt), is composed of large, complexly related, blocks of tuff.

The red lithic tuff is highly jointed, with many of the joint surfaces showing slickensides, and some having a coating of gypsum.

The red lithic tuff overlies the oldest rhyolite flow and breccia unit (Tr₂) on the mountain, and, as discussed previously, is complexly related to the trachytic tuff (Ttt). The lower units of the tuff are intercalated with the phenocryst- and lithic-rich tuff (Tpl). The red lithic tuff is included as blocks in laharic breccias that are exposed near the base of the air-fall and water-worked tuff (Tat; p. 64) east of the main part of Stonewall. The red lithic tuff is overlain by, intruded by, and faulted against, a series of rhyolite flows and domes (Tr₂; p. 70) that crop out along
the southeastern margin of the map area. The red lithic tuff has also been intruded by, brecciated, and included as lithic fragments within rhyolite necks that are exposed near the center of the mountain (Trsv; p. 72) and along the northeastern edge of the mountain (Trv; p. 71). The red lithic tuff has been intruded, along steep sharp contacts, by all the phases of the anorthoclase-bearing monzonite and syenite (Tms$_{1-4}$). The red lithic tuff is also locally faulted against these intrusions. No western or southern limits for the extent of the tuffs has been established, as the tuff continues for an unknown distance under a mantle of alluvium.

Interpretation of the Ash-flow Tuffs and Related Units

The first tuff to be extruded from the Stonewall Mountain volcanic center was the trachytic tuff (Ttt). This unit was apparently confined to areas west and south of rhyolite flows and breccias which had been erupted prior to the principal activity of the volcano. Shortly after extrusion of the trachytic tuff, after compaction but while the tuff still retained enough heat to deform plastically into the small scale folds that are locally preserved, the first episode of collapse in the volcanic center probably occurred. This collapse, triggered by emptying of part of the magma chamber, fractured the trachytic tuff into blocks that are 10 to 100 m. across.

Rhyolite breccia, vitrophyre, and flows were intruded and extruded along the western edge of the trachytic tuff. These rhyolites (Trb) are laterally discontinuous, and may have been localized by either fracture systems associated with collapse, topographic relief resulting from collapse, or a combination of both.
Emplacement of the rhyolite was followed by extrusion of a phenocryst- and lithic-rich tuff (Tpl), west of the trachytic tuff and into the area along the contact between the trachytic tuff and the older rhyolites and breccias. The easternmost exposure of the phenocryst and lithic-rich tuff is intercalated with the lower portion of the red lithic tuff (Trlt), indicating either that more than one volcanic vent was active at nearly the same time, or that the magma chamber was being tapped at 2 levels at the same time. The difference in phenocryst and lithic content between these units, however, suggests that a combination of the two processes was taking place.

The sequence of air-fall and welded ash-flow tuffs (Twt) exposed in the southeast corner of the mountain is most likely associated with the lower part of the red lithic tuff (Trlt). Although brecciated and locally altered, these tuffs (Twt) do not appear to have the chaotic orientations that are typical of the red lithic tuff in the center of the mountain; they may therefore represent units which are beyond the area of collapse. It is possible that tuffs and flows exposed along the southwestern margin of the mountain (Tts) occupy a stratigraphic position similar to those along the southern margin; however, these tuffs (Tts) may be younger than the main tuff sequence.

The major part of the red lithic tuff was emplaced as a series of compound cooling units over the collapse terrain of the trachytic tuff. The red lithic tuff thins dramatically over the oldest
rhyolite flow and breccia unit (Tr₁), which suggests that the rhyolites were a positive area at the time of emplacement of the red lithic tuff. Rapid emplacement, eruption of tuffs from multiple vents (if lithic-rich and lithic-poor tuffs did not come from the same vent), and localized collapse as a result of withdrawal of magma from the underlying chamber would have combined to create the thick compound cooling units suggested by the presence of thin, less densely crystallized zones in several areas. As many as 12 individual flows may be present (in the thickest portion of the tuffs, the total may be much higher). Where preserved, the basal vitrophyre (Fig. 8) is deformed; this may be a product of collapse while still warm.

The apparently conformable and unconformable relations between the trachytic tuff (Ttt) and the red lithic tuff (Trlt) may be a result of emplacement of the younger tuff over the collapse terrain. After collapse, the direction of attitudes on eutaxitic structures in the trachytic tuff may have been horizontal in some places and vertical in other places; where horizontal, the younger red lithic tuff would appear conformable. Absence of basal zones in red lithic tuff may indicate that at the time of its emplacement, the trachytic tuff was still warm, and "normal" cooling was prevented from taking place.

The vitric and unwelded zones in the red lithic tuff occur near the margins of Stonewall; this suggests that cooling breaks between units exist there. A similar pattern of compound cooling
units forming within a volcanic center with separation of sheets, as well as thinning of tuffs away from the volcanic source, has been noted in source complexes of the Caetano Tuff (Wrucke and Silberman, 1976), the southwestern Nevada Volcanic field (Byers, 1977; Christiansen, 1976), and the calderas of the San Juan volcanic field in Colorado (Lipman, 1975). Post-emplacement collapse of the red lithic tuff is indicated by the generally steep attitudes of eutaxitic structures. This collapse was local; in some areas the red lithic tuff is approximately horizontal over the older units. The strike of the tuff units on Stonewall generally describes a circular pattern around the mountain (Figure 9). This suggests that these units may have been confined within some physiographic feature - possibly a caldera wall and ring-fracture zone.

Cornwall (1972, p. 25) noted that: "There welded tuffs have been identified only on Stonewall Mountain." Ashley (personal communication, 1976) concurs and reported that recent mapping in the Ralston area did not reveal any tuffs that could be related to units on Stonewall. The tuffs of Stonewall may extend southwest, under the alluvial cover, or southeast, along and under the prominent mesa. Stonewall Mountain tuffs, however, were probably largely confined to the area of the mountain by collapse of the magma chamber during emplacement of the tuffs (similar to the Timber Mountain volcanic center, Christiansen, et al., 1977), or from viscous emplacement of the tuffs, in a manner similar to that depicted by McKee (1974).
Figure 9. Rose diagrams showing direction of strikes for compaction directions of ash-flow tuffs from different sections of Stonewall. The bars in each diagram are scales to indicate the number of readings in each direction.
Vents for the welded tuff units have not been identified. Anticipated features of source areas, such as steeply inclined eutaxitic structures grading into more or less horizontal attitudes (Walker, 1969; Cook, 1968), or zones of densely welded tuff surrounded by vitrophyre that widen upward and have shattered adjacent wall rock (Ekren and Byers, 1976), have not been found. Several causes for the lack of identifiable tuff vents are possible (Smith, in Ekren and Byers, 1976): vents may be covered by the extruded units, obliterated by erosion, filled with lava, or destroyed by caldera collapse. On Stonewall, another possibility exists: the vent areas may now be the sites of monzonite or latite intrusions. Since the tuffs are thick, lithic-rich, locally brecciated, altered to some degree, and have chaotic steeply dipping compaction directions, it is reasonable to assume that they are endogeneous to the Stonewall Mountain volcanic center (see McKee, in Wrucke and Silberman, 1976). The tuffs have been intruded by monzonites, which may have caused some doming and uplift in the collapsed area. Some of the slickensides which are found along joints in the tuffs may be related to this doming.

MONZONITES AND RELATED UNITS

Introduction

Two major intrusive units are exposed on Stonewall: a monzonite that crops out along the north and northwest margins of the mountain (map unit Tm), and a multiple intrusion of porphyritic monzonite and that crops out in the central and southern portions of the mountain
Monzonites account for about 13 percent of the surface exposures on Stonewall.

Monzonite (Tm)

A gray to orange-brown monzonite with feldspar, quartz, and biotite phenocrysts in a microcrystalline groundmass is exposed along the northern margin of Stonewall (map unit Tm). Near the edge of the mountain this monzonite typically is finer grained and more highly altered. This monzonite has been dated by the K-Ar method (samples 89 and 53), and a partial chemical analysis (sample 89) is included in the chemical data.

The monzonite has locally undergone argillic alteration. Quartz veins and black and white calcite veins cut the pluton. The quartz veins are especially well developed along the north edge of the mountain, where they are as much as 4 meters thick. These quartz veins typically are parallel to the front of the mountain. Minor gold and silver mineralization is present in this monzonite where it has intruded the Precambrian carbonates. The monzonite is highly jointed; several of the large veins follow pre-existing fractures.

The monzonite has phenocrysts of orthoclase, plagioclase, and biotite in a microcrystalline groundmass of potassium feldspar and quartz. The orthoclase occurs as euhedral to subhedral twinned phenocrysts as much as 7 mm. in length and commonly altered to sericite. Phenocrysts of plagioclase (andesine) are euhedral to subhedral, broken, have rims of sanidine, are as much as 1 cm. in length, and typically are altered to calcite and sericite. Biotite occurs
in laths to 4 mm.; although some is fresh, alteration to chlorite and opaques is common. Phenocrysts comprise less than 25 percent of the rock; of this proportion, orthoclase accounts for 80 percent, with plagioclase and biotite about 10 percent each. Potassium feldspar forms about 70 percent of the groundmass, typically as 0.2 mm. subhedral to euhedral micro-phenocrysts which are nearly totally replaced by sericite. Quartz forms about 20 percent of the groundmass. Biotite, in 0.2 to 0.4 mm. laths, which are locally altered to chlorite, forms 5 percent of the groundmass. Accessory minerals include zircon, monazite, apatite, and hornblende that is typically altered to opaques.

The monzonite truncates structural trends in the pre-Tertiary rocks as well as in the older andesites, rhyolites, and ash-flow tuffs. In several areas, large fragments of these older units are incorporated within the monzonite. Contacts of the monzonite with these other units are typically steep and sharp. This, combined with the fine-grained groundmass of marginal phases of the intrusion, and emplacement into volcanic rocks from the same or a closely related magma chamber, indicates that the monzonite was emplaced at a high level.

Anorthoclase-bearing Monzonite and Syenite (Tms)

A sequence of monzonite and syenite, characterized by anorthoclase phenocrystals that typically have anorthoclase rims, is found along the central and southern portions of the mountain. Rock names are based on Streckeisen's (1976) classification. The dominant rock unit in the central portion of the mountain is a light brown
coarse-grained monzonite (T_{ms_1}). A fine-grained phase of this monzonite occurs locally found along the margin of the coarse phase (T_{ms_2}). A syenite is exposed along the western edge of the mountain, and also forms an isolated hill west of the mountain (T_{ms_3}). A less silicic phase of the monzonite (T_{ms_4}) is intrusive in the southeast part of the mountain, and has been correlated with an extrusive unit toward the northeast; this is discussed later.

The monzonite in the central part of the mountain (map unit T_{ms_1}) has been sampled for both chemical analysis and age dating (sample 121). It is a massive but jointed pluton which typically has steep and sharp contacts with the surrounding tuffs.

Inclusions of brecciated tuff in marginal phases of the monzonite occur sparsely. The monzonite is cut in at least one place by a high angle fault.

Anorthoclase, plagioclase, and biotite are the major phenocrysts and are set in a feldspar-rich groundmass. The anorthoclase (identified optically) is present as 1-5 mm. euhedral to subhedral single or glomeroporphyritic phenocrysts that are fractured and embayed. The phenocrysts commonly have 0.1 to 0.2 mm. wide rims of anorthoclase with opaque inclusions. Such rims are also characteristic of the 2-5 mm. laths and phenocrysts of plagioclase (andesine). Braid antiperthites occur in the plagioclase. Plagioclase phenocrysts are occasionally included in the anorthoclase phenocrysts. Corroded phenocrysts of biotite (up to 3 mm.) and clinopyroxene (up to 1.5 mm.) are also present.
Figure 10 is a photomicrograph from this unit. Phenocrysts form about 40 percent of the rock; of this amount anorthoclase is 60 percent, plagioclase 30 percent, and mafics form less than 10 percent. The groundmass of the rock consists of 0.02 to 0.2 mm. grains of feldspar, minor quartz, and accessory sphene as well as secondary biotite, chlorite, epidote, and sericite.

Associated with, and often adjacent to, the coarse phase of the anorthoclase-bearing monzonite is a finer-grained darker-colored monzonite (map unit Tms\(_2\)). This unit was sampled for chemical analysis (sample 104). This monzonite is characterized by anorthoclase phenocrysts that are less than 2 mm. in length, set in a fine grained groundmass. This finer-grained phase is locally as much as 300 m. wide although it is generally narrower. Contacts between the fine monzonite and the red lithic tuff are sharp; however, the fine groundmass and similar color occasionally makes identification of the contact between the monzonite and the trachytic tuff difficult.

The finer-grained monzonite (Tms\(_2\)) is composed of anorthoclase, plagioclase, and slightly to heavily altered mafic phenocrysts in a feldspar-rich groundmass. The anorthoclase makes up about 50 percent of the rock, is anhedral, 0.2 to 3.0 mm. in length, and characteristically has rims of anorthoclase similar to those in the coarse monzonite. Locally, the anorthoclase phenocrysts enclose subhedral phenocrysts of sanidine. Plagioclase makes up less than 10 percent of the rock, is lath shaped, up to 2 mm. long, and has rims of anorthoclase. Biotite in flakes to 3 mm. that are locally
Figure 10. Anorthoclase-bearing monzonite (map unit Tms₁), showing rim of anorthoclase on anorthoclase phenocryst that is at extinction. The groundmass is predominantly composed of anorthoclase, with minor quartz. Crossed nicols, dimensions as Figure 7.
replaced by opaque minerals, and clinopyroxene that is altered to epidote and carbonate, are the mafic phases and account for about 3 percent of the rock. The groundmass is composed of 0.2 mm. grains of potassium feldspar, quartz, and plagioclase, accessory apatite, and a fine opaque dusting. Sericite occurs between grains and along fractures within grains.

A syenite (Tms₃) that is exposed along the western edge of Stonewall intrudes the red lithic tuff (Trlt) with which it has steep sharp contacts; it also intrudes the ash-flow tuff and lava flow unit (Tts) along a steep contact that is locally difficult to identify. This unit has been sampled for chemical analysis (sample 98).

About 30 percent of the unit is formed of phenocrysts. Euhedral to subhedral 0.5 to 5.0 mm. long crystals of anorthoclase with anorthoclase rims are dominant; resorbed 1-2 mm. plagioclase with anorthoclase rims, and clinopyroxene which has been partially replaced by opaques, are both subordinate. Quartz, as a phenocryst, is limited to reaction areas around the sparse quartzite inclusions. The groundmass consists of feldspar and quartz (?), with a fine dusting of opaque minerals, and secondary sericite, epidote, carbonate, hematite, and rutile.

A less silic anorthoclase-bearing monzonite crops out along the south and east margins of Stonewall (map unit Tms₄). The less siliceous nature of this unit has been established by chemical
analysis (sample 26, Chapter 3); its relation to the other monzonites already discussed is established by the presence of anorthoclase phenocrysts with anorthoclase rims. This unit is typically darker colored and has more vugs in the groundmass than do the other monzonites.

In thin section, this unit (Tms₄) is characterized by subhedral to euhedral fractured phenocrysts of anorthoclase, which reach 5 mm., and glomeroporphs of plagioclase and pyroxene. Two distinct sizes of phenocrysts are present - those larger than 1.5 mm., and those smaller than 0.5 mm.. The larger phenocrysts include anorthoclase, plagioclase, and sparse mafics, and account for about 25 percent of the rocks. Over 75 percent of the phenocrysts are anorthoclase; plagioclase with anorthoclase rims accounts for most of the remainder, with sparse clinopyroxene and biotite that have been altered to opaques and sericite (?). The smaller phenocrysts form less than 10 percent of the rock, with approximately equal amounts of anorthoclase and plagioclase. Epidote and chlorite are present as alteration products in the phenocrysts. The groundmass of the unit is composed of microlites of plagioclase, and an opaque dusting.

The less silicic anorthoclase-bearing monzonite intrudes the light colored monzonite (Tms₁). Contacts between these units are sharp and steep. The monzonite also intrudes, in its southern exposures, the red lithic tuff. The northern-most outcrop of rocks with phenocrysts similar to the monzonite is apparently exposed as a lava flow over rhyolitic tuff and air-fall tuff.
The rhyolite (Trht) that underlies the flow that has tentatively been correlated with the less silicic anorthoclase-bearing monzonite has phenocrysts of quartz, potassium feldspar, and plagioclase in an aphanitic groundmass that is slightly altered to clay minerals. An outcrop of air-fall tuff is exposed overlying the rhyolite flow; this tuff is tentatively correlated with thick air-fall and water-worked tuff exposed east of Stonewall. Lithics in both the rhyolite and the air-fall tuff are derived from the red lithic tuff that caps the mountain.

The less silicic anorthoclase-bearing monzonite is marked by a sub-horizontal joint set, with 1-2 meter spacing between joints. The rock has locally been cut by high angle faults.

Latite Breccia (Tbs)

Another extrusive unit tentatively correlated with the anorthoclase-bearing monzonites is latite breccia (map unit Tbs), which is confined to an area along the margin of the older tuff and flow unit (Tts) at the southwestern corner of the mountain. It is composed of angular flow-banded blocks of vesicular latite, as much as 10 meters by 3 meters, in a matrix of similar composition. The unit is jointed and is cut by steeply dipping faults along which breccias are located.

About 20 percent of the rock is subhedral sanidine phenocrysts, typically 2-3 mm. long. Corroded biotite, which is replaced by magnetite and feldspar, is present as phenocrysts to 5 mm., and accounts for 5 percent of the rock. Anhedral xenocrysts
of orthoclase, angular phenocrysts of plagioclase, and pyroxene (aegirine-augite?) replaced by opaques, and resorbed glomeroporphy of plagioclase and clinopyroxene compose about 10 percent of the rock. The feldspars typically have rims of sanidine-anorthoclase. The groundmass is composed of potassium feldspar, a crystallite too small to identify, secondary biotite, and opaques. The rock plots as a latite in Streckeisen's 1976 classification.

The presence of rimmed feldspars, the large biotite phenocrysts, and the pyroxene-plagioclase glomeroporphy are features typical of the anorthoclase-bearing monzonite and syenite. This latite, therefore, is tentatively considered to be an extrusive equivalent of the same magma, and may have preceded emplacement of the monzonites.

Interpretation of the Monzonites

The intrusive units of Stonewall were emplaced after the last collapse episode associated with extrusion of the red lithic tuffs. The intrusive rocks were not affected by the collapse episodes, which are reflected in random strike directions of joints in the tuffs (Figure 11). Contact relations, emplacement of the intrusive rocks into overlying volcanic rocks, and local extrusive equivalent units suggest that emplacement of the monzonites and syenite was very shallow. At least 600 m. of ash flow tuff is preserved above the anorthoclase-bearing monzonite. If the original thickness of the tuffs was double this amount, monzonites would have been emplaced at a depth slightly greater than 1 km.
Figure 11. Rose diagram showing strike direction for joints in the ash-flow tuff sequence. Most of the joints dip steeply. The bar scale indicates two readings.
The generally linear outcrop pattern of the monzonites and the pattern of joints within the intrusive units may reflect the control of regional stress patterns on magma emplacement at Stonewall (Figure 12). The strike directions of the Basin and Range faults along the north and west sides of the mountain (N65E and N5W) are approximately parallel to strikes of joints in the intrusions. The regional stress pattern that created the Basin and Range faults, and which is reflected in the directions of strikes of joints in the monzonites, may have created zones of weakness along which the monzonites were partially emplaced. Distribution of the intrusive rocks along the margins of Stonewall may suggest that their emplacement was in part controlled by the development of a ring fracture zone around the area where collapse of the tuffs took place. An outlying hill of anorthoclase-bearing monzonite west of Stonewall suggests that the ring fracture zone may, in part, be outside the present limits of the mountain. Ash-flow tuffs may be preserved outside the ring fracture zone on the southwest and the southeast corners of Stonewall. The absence of intrusive rocks near the northeast corner of the mountain suggests that this area may have been a breach zone in the ring (see cross-section A-A').

**LATE VOLCANIC UNITS**

**Andesite (Tad)**

A thick, dark gray, massive andesite is exposed along the southern edge of the monzonite in the northwestern part of the mountain (map unit Tad). This andesite was collected for both
Figure 12. Rose diagram showing strike directions for joints in the intrusive rocks. Most of the joints have steep dips. The bar scale indicates two readings.
chemical analysis and K-Ar age dating (sample 48). The andesite has local inclusions of rhyolite sediments similar to map unit Tmr; these inclusions are locally more than 5 m. in diameter.

The andesite contains plagioclase, amphibole, and pyroxene phenocrysts. The plagioclase (labradorite) forms 0.5 to 4.0 mm. laths in sub-parallel orientation, and shows some alteration to sericite and epidote along cleavage. The plagioclase forms less than 15 percent of the rock. About five percent of the rock is composed of euhedral, 0.5 to 1.0 mm. phenocrysts of clinopyroxene (aegerine?), which generally are altered to epidote, chlorite, carbonate, and opaques. Some phenocrysts have an amphibole rim. The groundmass of the andesite is composed of microlites of plagioclase, a fine grained opaque dust, and sericite. Flow-banding textures were apparent in one sample collected from the margin of the andesite.

The andesite is in contact with the phenocryst- and lithic-rich tuff (Tpl), the rhyolite and sedimentary unit (Tmr), the monzonite intrusion (Tm), the trachytic tuff (Ttt), and the Wyman Formation. No evidence has been found in the field to suggest that these contacts have been faulted. In several areas along the southern margin of the andesite, the phenocryst- and lithic-rich tuff has apparently been brecciated and altered by emplacement of the andesite. If the rhyolite and sedimentary rocks (Tmr) are intercalated with the phenocryst- and lithic-rich tuff (Tpl), and if the correlation of the large inclusion within the andesite with these rhyolites is correct, then the andesite would be younger than both the phenocryst-
and lithic-rich tuff and the rhyolite. The andesite may then be interpreted as either a dike that has cut through the older units, or a sill that was intruded parallel to compaction directions in the phenocryst and lithic rich tuff.

If the andesite is a dike, it would have been emplaced at least after the first episode of collapse associated with the thick ash-flow tuff sequence, because attitudes of eutaxitic structures in tuff adjacent to the andesite are steeply dipping. If the andesite was emplaced as a sill, most likely it would have been synchronous with extrusion of the tuffs; since it is now vertical, the change in orientation from horizontal could have resulted from one of the collapse episodes.

Either the dike or sill hypothesis is compatible with the ambiguous relations between the andesite and the monzonite (Tm). This contact is steeply dipping, and no clear age relation between the andesite and the monzonite could be established in the field. K-Ar data (chapter 4), however, suggest that the andesite is younger.

Airfall Tuffs and Rhyolites (Tat)

Two rock units that cannot, on the basis of their field relations, be placed in definite stratigraphic sequence, are an air-fall tuff and water-worked tuff unit (map unit Tat), and the thick sequence of rhyolite flows and domes that overlies it (map units Trf₁ and Trf₂). These are exposed along the eastern margin of the mountain.

Two main areas of exposure of the tuffs are along the northeast and southeast corners of the mountain. It is probable that the air-
fall and water-worked tuffs continue beneath the alluvium between their main outcrop areas.

The air-fall and water-worked tuffs (Tat) are about 150 m. thick, and typically have beds from one cm. to more than one m. thick. Channels in the tuff indicate the presence of water. The unit is fresh, yellow, unwelded, and contains lithic fragments from several units on Stonewall. The lower portion of the tuffs contains several breccias which are locally well indurated; and composed of poorly sorted, subangular to angular blocks, rarely as large as 1.5 m. diameter, of the lithic tuff unit that caps Stonewall. Although individual breccia zones are tabular, they lack internal bedding. The breccias have characteristics similar to those described by Fisher (1960) as typical of lahars in Washington; the breccias on Stonewall Mountain are therefore considered to be lahars.

The tuffs have widely spaced joints, and locally are cut by steep faults that have about 3 m. displacement. Quartz veins that outcrop in the northeastern exposure of lithic tuff are not found in adjacent exposures of air-fall and waterworked tuff.

The tuffs contain approximately equal amounts of quartz and sanidine. Together, these grains form about 10 percent of the rock. The quartz is rounded, embayed, and reaches 3 mm. The sanidine is subhedral, fractured, and typically 1-2 mm. long. Rare laths of plagioclase and altered pyroxene are also found as phenocrysts. The phenocrysts are similar to those in the lithic fragments in the tuff, and may have been derived from the accidental fragments during
deposition of the tuff. The lithic fragments are typically well-rounded and less than 1 cm. in diameter. The red lithic tuff (Trlt) that caps the mountain is the most abundant fragment with trachytic tuff (Ttt) and some intrusive, quartzite, and rhyolite vitrophyre rock fragments also present. The groundmass of the tuff is vitric, with microlites of feldspar (?) and quartz (?) as well as secondary biotite, hematite, sericite, chlorite, and carbonate.

Relationships between these air-fall and water-worked tuffs and adjacent volcanic units on Stonewall are obscured by talus. An outcrop of lithic-rich unwelded tuff occurs stratigraphically below flows associated with the anorthoclase-bearing monzonite (Tms4); this outcrop is tentatively correlated with air-fall and water-worked tuffs. Activity forming the tuffs and the laharic breccias may, on this evidence, pre-date the intrusion of the anorthoclase-bearing monzonite (Tms4).

Explosive volcanism generating the air-fall and water-worked deposits may have accompanied the rise of magma that cooled to form units Tms1 and Tms2. Disturbance of the topography, combined with locally heavy precipitation, might have led to conditions appropriate for the formation of lahars from debris on the mountain slopes.

Cornwall (1972, p. 25) regarded the air-fall and water-worked tuff (Tat) as younger than the main sequence of tuffs (Ttt; Trlt) that dominate Stonewall, and Ashley (1974, p. 21) suggested that the air-fall and water-worked tuff might be correlative with the Siebert Formation. The Siebert Formation, as described by Albers and
Stewart (1972, p. 34), is restricted to outcrops in the Tonopah district of the Goldfield area. In the Tonopah district, the Siebert Tuff unconformably overlies the Fraction Tuff, and is intruded by the Brougher dacite (Bonham and Garside, 1974, p. 45). The Fraction Tuff has yielded a K-Ar date of 17 m.y., the Siebert Tuff has a K-Ar date of $15.5 \pm 1.6$ m.y., and the Brougher Dacite has been dated at 16.2 m.y. (Silberman and McKee, 1972). All of these dates are much older than is reasonable for the air-fall tuff east of Stonewall, assuming deposition of the tuffs is close in time to the intrusion of the anorthoclase-bearing monzonite, about 7.5 m.y. b.p. (see chapter 4). The Esmeralda Formation, an air-fall tuff cropping out is Esmeralda County, ranges in age from 13.1 to 4.3 m.y. (Robinson et al., 1968). The Esmeralda Formation is restricted, however, to exposures in the Silver Peak area (Robinson et al., 1968, Albers and Stewart, 1972) and this term seems inappropriate for the outcrops adjacent to Stonewall. Cornwall (1972), in summarizing the geology of the southern Nye County, mentions neither the Siebert nor the Esmeralda Formations. It is therefore suggested that the ash-fall and water-worked tuff adjacent to Stonewall be considered a local unit. Similar air fall tuffs are found within or adjacent to other volcanic centers (Byers et al., 1976; Robinson, 1972).

The lower contact of the tuffs is not exposed; they are overlain by a 300 m. thick sequence of rhyolite flows and domes (map units Trf1&2).
The rhyolites ($\text{Trf}_1$ and $\text{Trf}_2$) are light gray and vuggy. The rhyolite has been divided into two units: unit 1 has rare mafic phenocrysts; unit 2 does not have mafics. Rare basalt xenoliths are found. Individual flows are as much as 2 m. thick, but average less than 1 m. in thickness. Flow banding within units is developed at 3-20 cm. intervals. The flow banding is locally highly controlled; its attitudes may vary greatly over several meters.

Phenocrysts of sanidine, quartz, plagioclase, and biotite form 15 percent of the rhyolites. Fifty percent of the phenocrysts consist of euhedral to subhedral, embayed, fractured, and rarely twinned sanidine. Twenty-five percent of the phenocrysts are quartz, which are less than 1 mm., embayed, rounded, and contain magnetite, zircon, and abundant fluid inclusions. Lath shaped biotite phenocrysts are less than 1 mm. long, and typically show some alteration to iron oxides. Plagioclase (oligoclase) is present as both phenocrysts and glomeroporhps. The phenocrysts are twinned, rarely zoned, subhedral to euhedral, and about 0.5 mm. long. A second, xenocrystic (?) potassium feldspar is greater than two mm. in diameter, and extensively fractured. Sphene is an accessory mineral. The groundmass is formed of spherulitic devitrified brown glass. Magnetite dusting throughout the quartz-feldspar devitrification products is common. About 5 percent of the phenocrysts in unit 1 are biotite, whereas less than one percent of the phenocrysts in unit 2 are biotite.

The lower contact of the rhyolite flows is marked by a rhyolite breccia, and locally obsidian is found. The upper contact is not
exposed. These rhyolites have been estimated to be about 1300 feet (400 m.) thick, and are in fault contact along their east side with the Thristy Canyon Tuff (Ekren et al., 1971, p. 58). Small steeply-dipping faults cut the rhyolites.

Units Exposed with the Air-fall Tuffs (Tb, Tv, Tbm)

Isolated outcrops of basalt (map unit Tb), vitrophyre (map unit Tv) and a trachyte flow (map unit Tbm) occur within the area of the airfall tuffs described above.

A basal scoriaceous breccia occurs where the basalt (Tb) fills depressions in the underlying tuffs. Basalt similar to this flow is apparently incorporated in the thick rhyolite dome adjacent to the airfall tuffs; however, alluvial debris obscures relations and does not permit exclusion of the possibility that the basalts overlie the rhyolite.

The basalt has lath shaped plagioclase (labrodorite) phenocrysts to 1.5 mm. long and 0.2 to 0.3 mm. average diameter olivine phenocrysts altered to iddingsite along fractures. The groundmass is composed of sub-parallel microlites of plagioclase, clinopyroxene, altered olivine, and apatite.

The basalt (Tb) is apparently capped by a trachyte flow (Tbm). Sanidine, quartz, and plagioclase phenocrysts are present in the flow. The sanidine is subhedral, fractured, up to five mm. long, and has poikilitic inclusions of plagioclase. Phenocrysts of quartz are less than 0.5 mm., and deeply embayed. Plagioclase grains are up to 1.5 mm. long. Opaque minerals have replaced amphibole (?)
phenocrysts. Rutile is conspicuous in the groundmass, which is a brown glass with crystallites of quartz (?) and feldspar (?). Sericite and carbonate are alteration products along fractures and rarely replacing phenocrysts.

Outcrops are not adequate to establish stratigraphic relations between the basalt and trachyte, and a brown vitrophyre (Tv). Phenocrysts of sanidine, quartz, and plagioclase account for about 25 percent of this vitrophyre. Sanidine and quartz each form about 40 percent of the phenocrysts, plagioclase makes up the rest. All of these phenocrysts are anhedral, fractured, and slightly resorbed. Minor pigeonite is present. The groundmass has many 0.05 to 0.1 mm. spherulites, as well as less than 0.5 mm. microphenocrysts feldspar. Sericite and calcite are rare. Glomeroporphs of plagioclase and sanidine, as well as volcanic, intrusive, and siltstone fragments are present.

The basalt is probably of local origin, the vitrophyre may be correlative with the rhyolite described immediately below; the source for the trachyte flow has not been identified.

Rhyolite (Tbm)

A flow-banded rhyolite crops out along the southeast edge of the mountain (map unit Tr2). The rhyolite is marked by a local 7 m. thick basal breccia of subrounded to rounded 1 cm. to 1 m. pumice fragments in a rhyolite matrix. This breccia is overlain by a zone of black vitrophyre that grades upward into a rhyolite flow. Near the east margin of the rhyolite flow, some tuffs are apparently
locally intercalated with the rhyolite. The rhyolite includes several 10 m. diameter dome-like outcrops, which apparently intrude the flow-banded quartz- and sanidine-rich rhyolite.

Less than 10 percent of the rhyolite consists of phenocrysts. Of these, more than 50 percent are subhedral embayed quartz, mostly 1 to 2 mm. long. Sanidine forms about 30 percent of the phenocrysts and plagioclase the remaining 20 percent. Mafics, altered to hematite, are rare. The groundmass is vitric, with a few spherulites and local patches of secondary sericite.

The rhyolite is faulted along its western contact with the lithic tuff; other contacts are obscured by debris. It seems likely, however, that the rhyolite is at least in part younger than the air-fall tuff (map unit Tat), if correlation of this rhyolite with map unit Tv is correct. The rhyolite has apparently deformed the originally horizontal tuffs so they are now dipping as much as 26°. Along the southeast corner of the mountain, rhyolite flows that overlie the red lithic tuff (Trlt) have tentatively been correlated with these rhyolite intrusions.

Late-Stage Rhyolite Necks (Trv, Trsv)

A series of three small rhyolite necks (map unit Trv) intrude both the highly altered rhyolite (Tr₁) and the red lithic tuff (Trlt) along the northeast margin of the mountain. These rhyolites have been sampled for chemical and K-Ar analyses (sample 143). The largest plug, about 10 m. by 15 m. has an outer zone of vitrophyre,
which is as much as 2 m. thick, enveloping a zone of quartz and
feldspar filled vugs and local development of geodes. The center
of the plug is steeply dipping flow-banded rhyolite.

Quartz, sanidine, plagioclase, biotite, and rare aegerine-augite
are the phenocrysts in this rhyolite. The quartz is rounded,
embayed, up to 4 mm. long, and composes about 5 percent of the rock.
The sanidine crystals are also rounded, smaller, and fractured grains,
and makes up about 8 percent of the rock. Broken laths of plagioclase
(oligoclase) are up to 1 mm. long. Unaltered biotite and aegerine-
augite each make up about 1 percent of the rock. The groundmass is
vitric, and shows some perlitic fractures.

The country rocks have been intruded and brecciated by the
rhyolites. The vertical orientation of the rhyolite plugs is
probably their primary attitude, and indicates that these rhyolites
post-date the episodes of collapse. These rhyolites are, on the basis
of their lack of alteration, the youngest unit on Stonewall. This
conclusion is also suggested by results of the K-Ar analyses...

Another rhyolite intrusion (map unit Trsv) crops out near the
geographic center of the mountain. This unit is much larger than the
small plugs described above, although it has many of the same
features. In good exposures, an outer vitrophyric zone, 2 m. thick,
grades into a 5 m. thick lithic-rich vitrophyre, which is transitional
toward the center of the unit into gray, steeply dipping flow-banded
rhyolite. The rhyolite intrusion has brecciated the surrounding lithic
tuff and prophyritic latite. Zenoliths of both are found in the rhyolite, and locally are as large as 1 by 2 m.

Phenocrysts of sanidine, quartz, plagioclase, and rare mafics total about 15 percent of this rock (Trsv). Seventy-five percent of these phenocrysts are sanidine and 20 percent are quartz. The sanidine forms rounded phenocrysts, usually less than 1.5 mm., the quartz forms embayed rounded grains with inclusions of groundmass material. Plagioclase and opaque minerals replacing amphibole are rare. The groundmass of quartz and feldspar, with fine-grained opaque dusting, exhibits flow banding.

The stratigraphic position of this rhyolite can not be definitely established. It is younger than the anorthoclase-bearing monzonite and the red lithic tuff, and may be as young as the rhyolite vitrophyres along the north edge of the mountain.

QUATERNARY UNITS

Debris mantles the slopes and valleys of Stonewall and was mapped as a separate unit where it was not possible to determine the lithology of the underlying rocks. Talus deposits (Qt) are found near the base of slopes; they are composed of poorly sorted blocks up to 10 m. across in a matrix of finer debris. Slopes underlain by red lithic tuff have a conspicuous talus mantle. Landslide deposits (Qls) cover some upper slopes and margins of valleys. Typically they are composed of several rock types in poorly sorted
deposits. The largest landslide is near the northeastern edge of the mountain where it covers altered rhyolite to depths of 20 m.. Older alluvium (Qoa) is poorly sorted debris along valley bottoms. Present stream courses have deposits of alluvium (Qal) similar to, but cutting through, the older alluvium. All of these units have been mapped as Quaternary deposits because of their relation to present topography.
CHAPTER 3
GEOCHEMISTRY

Introduction

The study of major-element and selected trace-element chemical analyses of the rocks from the Stonewall Mountain volcanic center was undertaken to:

1. Characterize the bulk chemistry of the igneous rocks of Stonewall,
2. Augment petrographic studies in understanding magmatic relations between the major igneous rock units, and
3. Compare Stonewall with other Late Miocene volcanic centers in western Nevada.

Geochemical sampling was done on a reconnaissance basis. Hand specimens were selected for analysis from the least altered outcrops of several of the major rock units on the mountain, as well as from several volumetrically less important rock units. The primary criterion for sample selection in the field was apparent lack of secondary alteration. Most igneous units on Stonewall show either some devitrification, or deuteritic, propylitic, or argillic alteration; these processes might have modified slightly the original rock composition.
Table 1. Results of the chemical analyses

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1 - total volatiles
48 - massive andesite dike or sill (map unit Tad)
58 - andesite (map unit Ta)
35, 38 - red lithic tuff (map unit Trlt)
76 - trachytic tuff (map unit Ttt)
98 - anorthoclase-bearing syenite (map unit Tms₃)
26 - anorthoclase-bearing monzonite (map unit Tms₄)
104 - anorthoclase-bearing monzonite (map unit Tms₂)
121 - anorthoclase-bearing monzonite (map unit Tms₁)
89 - monzonite (map unit Tm)
143 - rhyolite vitrophyre (map unit Trv)
Conclusions in this chapter are considered to be preliminary. Eight complete and three partial analyses may not be adequate for delineation of the entire range of rock compositions on the mountain, and they are insufficient to depict either original magmatic variations within each unit, or the effects of secondary alteration upon each unit.

Table 1 presents the results of the analyses; Figure 13 indicates the locations for each sample.

Analytic Methods

Samples 98 and 121 were determined by the U.S. Geological Survey facility for rapid rock analysis, following the techniques of Shapiro (1975).

For the other samples, analyses for total Fe, FeO, MnO, MgO, and P$_2$O$_5$ were done by A.S. McCreath and Son, using wet chemical techniques. It is not possible to estimate the precision of these analyses, but comparison of McCreath's analysis for sample 121 with that of the U.S.G.S. (Table 2) suggests that the wet chemical analyses for FeO, MnO, and MgO are fairly accurate.

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Figure 13. Location of samples selected for geochemical analyses.
The discrepancy in results for $\text{Fe}_2\text{O}_3$ and $\text{P}_2\text{O}_5$ may be a result of slight differences in composition between different hand samples analysed. The specimen submitted to the U.S.G.S. was not available when the sample was analyzed by McCreath; different samples from the same outcrop were required. Results of the chemical analysis used by McCreath for $\text{Fe}_2\text{O}_3$ may also have included minor amounts of Al and Ti.

$\text{SiO}_2$, $\text{Al}_2\text{O}_3$, $\text{TiO}_2$, and CaO concentrations were determined by X-ray fluorescence (XRF), following the method of Norrish and Hutton (1969). In sample 26, these elements were determined by A.S. McCreath and Son, using wet chemical methods. For the XRF analyses, glass discs were prepared by fusing 420 mg. of powdered sample, 30 mg. of $\text{NaNO}_3$, and 2.25 gms. of LaO flux (Chemplex, Grade III) in a 1050$^\circ$C. oven for 15 minutes, pouring the liquid onto graphite, and pressing to a disc. Total volatile content was determined by measuring weight loss in powdered samples after they had been heated at 1050$^\circ$C. for 15 minutes. The samples were analyzed on a Rigaku Geigerflex, using a LiF source for Fe, Ti, and Ca, and a PET source for Al and Si. The system was operated under vacuum; ten second counts were made. U.S.G.S. rock G-2 was run as a standard, with values calculated for U.S.G.S rock GSP-1 as an estimate of accuracy (Table 3).
Table 3
Comparison of published analyses with
determinations by XRF for selected
oxides in U.S.G.S. rock standard GSP-1

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Flanagan (1972)</th>
<th>This Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>67.38</td>
<td>67.81</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>15.25</td>
<td>15.14</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.66</td>
<td>0.72</td>
</tr>
<tr>
<td>CaO</td>
<td>2.02</td>
<td>2.07</td>
</tr>
</tbody>
</table>

Values determined for SiO₂ and Al₂O₃ are in generally good agreement with previously published data. Although minor differences exist in TiO₂ and CaO determinations, these differences are small when compared with the total sample, and do not affect the discussion below.

Results for analyses of selected elements in sample 98, which were determined by both the XRF method and the U.S.G.S. rapid rock facility allow comparison of the results for the methods (Table 4).

The values for SiO₂ and Al₂O₃ are in generally good agreement. Although percent differences between the U.S.G.S. and XRF analyses for TiO₂ and CaO are relatively large, the absolute amount of these elements present in the sample is small, and the analytical differences do not affect the discussion below. It should also be noted that, as was the case with comparison of the analyses by the U.S.G.S and McCreath, some variation between analyses might be a result of using different hand samples.
Table 4
Comparison of XRF analyses with determinations by the U.S.G.S. for selected oxides in sample 98

<table>
<thead>
<tr>
<th>Oxide</th>
<th>U.S.G.S.</th>
<th>XRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>65.5</td>
<td>66.32</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>16.9</td>
<td>17.1</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.50</td>
<td>0.47</td>
</tr>
<tr>
<td>CaO</td>
<td>1.0</td>
<td>1.14</td>
</tr>
</tbody>
</table>

K and Na were determined by single-channel flame photometry, using a Zeiss PF-5 photometer. Sample preparation followed the technique of Cooper (1963), and is described more fully in the discussion of K-Ar dating. Samples, with the exception of 58, were analyzed in duplicate, and U.S.G.S. rock standards G-2 and GSP-1 were run for comparison. Table 5 presents the results of these analyses. Values determined for the U.S.G.S standards are presented in Table 6.

Table 5
Precision of K & Na determinations

<table>
<thead>
<tr>
<th>Sample</th>
<th>K₂O mean</th>
<th>std. deviation</th>
<th>Na₂O mean</th>
<th>std. deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td>3.74</td>
<td>0.06</td>
<td>4.05</td>
<td>0.03</td>
</tr>
<tr>
<td>58</td>
<td>3.76</td>
<td>-</td>
<td>3.45</td>
<td>-</td>
</tr>
<tr>
<td>35</td>
<td>6.45</td>
<td>0.08</td>
<td>4.99</td>
<td>0.07</td>
</tr>
<tr>
<td>38</td>
<td>6.45</td>
<td>0.01</td>
<td>5.23</td>
<td>0.13</td>
</tr>
<tr>
<td>76</td>
<td>6.54</td>
<td>0.13</td>
<td>5.02</td>
<td>0.01</td>
</tr>
<tr>
<td>26</td>
<td>6.30</td>
<td>0.34</td>
<td>4.80</td>
<td>0.02</td>
</tr>
<tr>
<td>104</td>
<td>6.71</td>
<td>0.08</td>
<td>4.89</td>
<td>0.01</td>
</tr>
<tr>
<td>89</td>
<td>6.40</td>
<td>0.14</td>
<td>4.85</td>
<td>0.10</td>
</tr>
<tr>
<td>143</td>
<td>4.75</td>
<td>0.35</td>
<td>3.62</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Table 6
Comparison of values of K$_2$O and Na$_2$O reported in the literature with those determined in this study

<table>
<thead>
<tr>
<th></th>
<th>GSP-1</th>
<th></th>
<th>G-2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K$_2$O</td>
<td>Na$_2$O</td>
<td>K$_2$O</td>
</tr>
<tr>
<td>Flanagan (1972)</td>
<td>5.53</td>
<td>2.80</td>
<td>4.51</td>
</tr>
<tr>
<td>This study</td>
<td>5.52</td>
<td>2.92</td>
<td>4.51</td>
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</tbody>
</table>

Data in Tables 5 and 6 indicate that determinations of K$_2$O and Na$_2$O have good analytical precision. Na$_2$O determinations for the rock standards made during this study are slightly higher than published values for the standards. Error in making or calibrating the standard solutions against which the samples were run may have contributed to this difference.

Table 7
Precision of Rb & Sr determinations (values reported in ppm)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rb mean</th>
<th>std. deviation</th>
<th>Sr mean</th>
<th>std. deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td>105</td>
<td>0.71</td>
<td>753</td>
<td>8.5</td>
</tr>
<tr>
<td>58</td>
<td>125</td>
<td>0.71</td>
<td>905</td>
<td>4.9</td>
</tr>
<tr>
<td>35</td>
<td>80</td>
<td>4.2</td>
<td>257</td>
<td>4.9</td>
</tr>
<tr>
<td>38</td>
<td>101</td>
<td>x</td>
<td>203</td>
<td>x</td>
</tr>
<tr>
<td>76</td>
<td>116</td>
<td>x</td>
<td>58</td>
<td>0.5</td>
</tr>
<tr>
<td>98</td>
<td>93</td>
<td>x</td>
<td>77</td>
<td>x</td>
</tr>
<tr>
<td>26</td>
<td>95</td>
<td>x</td>
<td>355</td>
<td>2.8</td>
</tr>
<tr>
<td>104</td>
<td>95</td>
<td>1.4</td>
<td>163</td>
<td>2.1</td>
</tr>
<tr>
<td>121</td>
<td>88</td>
<td>1.4</td>
<td>214</td>
<td>0.4</td>
</tr>
<tr>
<td>89</td>
<td>96</td>
<td>0.7</td>
<td>297</td>
<td>0.7</td>
</tr>
<tr>
<td>143</td>
<td>266</td>
<td>2.1</td>
<td>37</td>
<td>x</td>
</tr>
</tbody>
</table>

x-duplicate analyses of these samples were identical to the closest ppm.
XRF analyses for Rb and Sr were made on pressed pellets prepared by powdering 3 gms. of sample to less than 200 mesh, packing with boric acid, and holding under 15 tons pressure for two minutes. The samples were analyzed in air; 100 second counts were taken on baselines, and 200 second counts were taken on K peaks. Samples were run in duplicate, and results calibrated against a known standard. Precision of the analysis is reported in Table 7.

Geologic Processes Which May Have Affected The Analytical Results

Although relatively unaltered, the chemical composition of the analyzed rocks may have been slightly changed by secondary processes. Secondary alteration might have produced changes in the oxidation state of Fe and Na values. Irvine and Baragar (1971), in adjusting chemical compositions of volcanic rocks to remove the effects of alteration, set an upper limit of %Fe$_2$O$_3$ = %TiO$_2$ + 1.5. Based on this criterion, the volcanic rocks analyzed on Stonewall, with the exception of sample 143, have an excess amount of Fe$_2$O$_3$. Lipman et al. (1969) found Fe was oxidized during devitrification of rhyolite flows. Fe$^{+3}$/Fe$^{+2}$ ratios are similar, however, to those reported from rocks with similar silica values by Noble et al. (1976) from the Eureka Valley Tuff, and Robinson (1972) from the Silver Peak volcanic center, indicating that such oxidation is common in volcanic units in western Nevada and California.

Scott (1966) found loss of Na, without loss of K, during weathering of slightly welded ignimbrites in eastern Nevada.
Whitebread (1976) illustrates loss of Na\textsubscript{2}O, CaO, Al\textsubscript{2}O\textsubscript{3}, and SiO\textsubscript{2}, and either loss or gain of K\textsubscript{2}O and MgO, as a result of hydrothermal alteration. Trace element data may also have been affected by secondary alteration. Rb, which follows K, might have either increased or decreased, and Sr, which follows Ca, might have decreased (Whitebread, 1976).

Quantitatively important changes produced in the rocks of Stonewall by secondary processes might include the oxidation of Fe and the lowering of Na\textsubscript{2}O concentration. With the limited number of analyses, however, it is not possible to quantify the changes in rock composition produced by secondary processes. In the discussion below, values reported for the analyses are assumed to accurately depict the original composition of the rock analyzed.

Chemical Classification of the Volcanic Rocks

Niggli norms have been calculated for the four volcanic samples (Table 8), following Barth (1952, pgs. 76-82), and have been used to classify the rocks following the method of Irvine and Baragar (1971). Figure 14 demonstrates that the volcanic rocks of Stonewall are in part of the field typically occupied by calc-alkaline rocks. On Figure 15, it can be seen that based on feldspar ratios, the volcanic rocks of Stonewall are "average" to "K-rich". Irvine and Baragar assign specific rock names on a basis of normative color index versus normative An content; on Figure 16 it can be seen that the more mafic rocks plot in the andesite field, the ash-flow tuff plots on the dacite-rhyolite join, and the
Table 8. Calculations of Niggli Norms (after Barth, 1952) for volcanic rocks on Stonewall. Sample numbers as on Table 1: Ap = apatite, Il = ilmenite, Or = orthoclase, Ab = albite, An = anorthite, Mt = magnetite, Wo = wollastonite, En = enstatite, Fs = ferrosilite, Qz = quartz

<table>
<thead>
<tr>
<th></th>
<th>48</th>
<th>58</th>
<th>38</th>
<th>143</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>0.72</td>
<td>0.55</td>
<td>0.19</td>
<td>-</td>
</tr>
<tr>
<td>Il</td>
<td>3.32</td>
<td>1.62</td>
<td>1.34</td>
<td>0.26</td>
</tr>
<tr>
<td>Or</td>
<td>13.3</td>
<td>14.55</td>
<td>23.2</td>
<td>16.35</td>
</tr>
<tr>
<td>Ab</td>
<td>21.95</td>
<td>20.3</td>
<td>28.55</td>
<td>19.2</td>
</tr>
<tr>
<td>An</td>
<td>14.96</td>
<td>20.5</td>
<td>4.56</td>
<td>2.84</td>
</tr>
<tr>
<td>Mt</td>
<td>1.89</td>
<td>1.42</td>
<td>1.31</td>
<td>0.20</td>
</tr>
<tr>
<td>Wo</td>
<td>3.6</td>
<td>1.52</td>
<td>2.46</td>
<td>0.12</td>
</tr>
<tr>
<td>En</td>
<td>6</td>
<td>0.68</td>
<td>2.82</td>
<td>3.08</td>
</tr>
<tr>
<td>Fs</td>
<td>3</td>
<td>2.04</td>
<td>0.46</td>
<td>0.50</td>
</tr>
<tr>
<td>Qz</td>
<td>31.12</td>
<td>36.76</td>
<td>35.04</td>
<td>57.21</td>
</tr>
<tr>
<td></td>
<td>99.86</td>
<td>99.94</td>
<td>99.93</td>
<td>99.76</td>
</tr>
</tbody>
</table>

Norm. Plag. $(\frac{100}{\text{An}})$

| 40.53 | 58.82 | 13.77 | 12.89 |

Color Index

$(\text{Ol}+\text{Opx}+\text{Cpx}+\text{Mt}+\text{Il}+\text{Hm})$

| 14.21 | 5.76  | 5.93  | 4.04  |
Figure 14. Weight percent $\text{Al}_2\text{O}_3$ versus Normative (Niggli) (100 An/An+ Ab) Plagioclase for analyzed volcanic samples. (-A = calc-alkaline, T = tholeiitic. Fields from Irvine and Baragar (1971), Figure 6. Numbers indicate sample numbers.)
Figure 15. An - Or - Ab diagram for analyzed volcanic samples, (numbers indicated). Sodic, average, and K-rich fields from Irvine and Baragar (1971), Figure 8.
Figure 16. Plot of normative color index \((\text{Ol} + \text{Opx} + \text{Cpx} + \text{Mt} + \text{Il} + \text{Hm})\) versus normative plagioclase for analyzed volcanic samples. Fields of basalt, andesite (and.), and tholeiitic andesite (thol. and.), dacite, and rhyolite (rhyo.) are from Irvine and Baragar (1971), Figure 7. Sample numbers are indicated.
vitrophyre plots in the rhyolite field. The ash-flow tuff is petrographically closer to a dacite than a rhyolite, and dacite is the preferred name. For the other samples, petrographic and chemical criteria suggest the same rock names, and these names have been employed throughout this study.

Classification of the Intrusive Rocks

Although samples 26, 98, 104, and 121 have been grouped on a petrographic basis as distinct phases of the anorthoclase-bearing monzonite and syenite which is dominant along the southern part of the mountain, comparison of chemical analyses for these rocks with those reported in Nockolds (1954) for average monzonite shows that the rocks of Stonewall have more SiO₂, K₂O, and Na₂O, and less CaO. Sample 26, except for slightly higher Na₂O and lower CaO, compares closely to Nockolds average calc-alkali syenite. Although the intrusive samples are much like Nockold's composition for granodiorite, petrographic analysis of the rocks shows that the rocks do not contain sufficient quartz or plagioclase to plot in the field labeled by Streckeisen (1976) as granodiorite. In following Streckeisen's classification of plutonic rocks, the term monzonite has been applied throughout this study.

Discussion of the Major-Element Data

The most notable chemical characteristics of the rocks of Stonewall is their high Na₂O and K₂O content. The absence of rocks with less than 58% SiO₂ is also unusual. The Black Mountain (Noble and Christiansen, 1974), Timber Mountain (Byers et al., 1976), and Silver Peak
volcanic centers are characterized by potassic and peralkaline volcanic rocks, and have exposures of lavas that are more mafic than any on Stonewall. Rocks that have been petrographically identified as basalts are exposed in isolated outcrops along the southeastern edge of Stonewall; these rocks may represent the more mafic part of the Stonewall magma. Without analyses, however, such a conclusion must be considered tentative.

K$_2$O and Na$_2$O concentrations in Stonewall rocks are generally similar to values reported from peralkaline volcanic rocks (Noble and Parker, 1974) and alkali granites (Nockolds, 1954). The rocks of Stonewall, however, have too much Al$_2$O$_3$ to be considered peralkaline; they fall instead into Shand's (1947) classification as metaluminous.

Plots of the data from Stonewall on AFM (Fig. 17) and KCN (Fig. 18) diagrams suggest, although they do not prove, that the rocks of Stonewall form a differentiation sequence.

On the AFM diagram, the data cluster near the iron-alkali join, and plot over too narrow a range to allow determination of whether general trends follow typical calc-alkaline, alkaline, or tholeitic variation patterns. There is a general trend of an increase in the relative amount of alkalis as silica increases. This trend is typical for rock suites, and does not aid in determining the variation pattern.
Figure 17. AFM diagram for volcanic and intrusive rocks of Stonewall. □ = andesites, △ = ash-flow tuff, ◇ = rhyolite, ○ = intrusions.
Figure 13. KCN diagram for volcanic and intrusive rocks of Stonewall. The symbols are the same as on the AFM diagram.
On the KCN diagram, the more silic samples cluster together, and are set slightly apart from the rocks with less than 59% SiO₂. Strong clustering of tuffs, intrusions, and rhyolite suggests that these rocks might be genetically related. Although the two andesites plot separately, their position on this diagram does not allow determination of whether they belong to the same, or a slightly different, magma. The data plot away from the CaO and MgO apices, suggesting that the rocks are fairly highly evolved.

Plots of the data on variation diagrams (Fig. 19) also suggest, but do not prove, that the rocks may be part of a differentiation sequence. Trends are similar to those reported by Robinson (1972) and Noble and Christiansen (1974) from the Silver Peak and Black Mountain volcanic centers, respectively. Absence of mafic samples, and a gap in silica values between 66% and 74% decrease the reliance that can be placed on the apparent trends.

Discussion of the Trace-Element Data

A plot of absolute values for Rb and Sr (Fig. 20) shows that the volcanic rocks of Stonewall fall in the andesite, dacite, and rhyolite fields, and overlap into the field reported for peralkaline rocks.

Rb values for Stonewall Mountain rocks are close to average values reported by Heier and Adams (1964) of 99 ppm (parts-per-million) in granodiorite and 97 ppm for dacite, although they are generally lower than values reported for monzonite (136 ppm) and trachyte (238 ppm). The rhyolite vitrophyre (sample 143) is slightly
Figure 19. Variation diagram for selected oxides (in weight percent) versus Silica for volcanic and intrusive rocks in the Stonewall Mountain center.
Figure 20. Plot of Rb versus Sr concentrations, in ppm, for volcanic rocks on Stonewall. The fields for rhyolites, dacites, and andesites are from Hedge (1966); the field of peralkaline rocks is from Ferrara and Treuil (1974).
enriched in Rb compared to the concentration (217 ppm Rb) reported by Heier and Adams.

Sr contents of Stonewall rocks are similar to those reported by Noble and Parker (1974) for rocks from the Black Mountain volcanic center, although they are much less than those reported by Robinson (1972) for rocks from the Silver Peak volcanic center.

Figure 21 is a plot of the Rb/Sr ratios of the volcanic and intrusive rocks against their differentiation index (Thornton and Tuttle, 1960). An increase in Rb/Sr ratio as the rocks become more differentiated is typical, and this trend is evident in the data from Stonewall.

K/Rb ratios for the tuffs and monzonites have a very small range, from 586 to 530. This range is higher than that of 374-176 reported by Noble and Parker (1974) on rocks of comparable SiO₂ value. The restricted and relatively high values for this ratio are suggestive that the rocks on Stonewall evolved from a single magmatic source.

K/Rb ratios in the andesites and rhyolites are lower (295-148), and are typical of the ranges reported from other volcanic centers.

Interpretations of the Data

The tuffs and intrusions are closely grouped on FMA, KCN, and variation diagrams, and have uniformly high K/Rb ratios. Abundances and ratios of oxides and elements in these rocks show little range
Figure 21. Plot of Rb/Sr ratio versus the differentiation index of Thornton and Tuttle (1960).
between samples; if more than one magma generated these rocks, the magmas would have undergone similar processes in a spatially and chronologically restricted environment. It is reasonable, therefore, to postulate only one magmatic source for these rocks.

Samples 48 and 58, which are less silicic than the other analyzed samples, apparently fall on trend lines with the other samples, although they have much lower $K_2O/Na_2O$ ratios and higher Sr values than the other rocks. This may indicate that samples 48 and 58 are from a less differentiated part of the magma that produced the tuffs and intrusions or that they are from a chronologically and spatially closely related, but chemically distinct, magma. The andesitic rocks form only a small part of the Stonewall volcanic center; large volumes of magma are not required to account for them.

Nearly synchronous emplacement of chemically distinct magmas has been postulated in several other volcanic and intrusive terrains. Robinson (1972) suggested that separate magmas were required to account for the chemical spectrum shown by the rocks of the Silver Peak volcanic center. Tilling (1973), in working with the much larger Boulder Batholith, postulated that two closely related magmatic series are needed to account for the intrusive and extrusive rocks of that area.

The rhyolite (sample 143) is the most silicic sample, and although it plots slightly away from the tuffs and intrusions on FMA, variation, and Rb-Sr diagrams, it is not necessary to postulate a second magmatic source to account for its composition. Higher
differentiation index, lower K/Rb ratio, and a higher Rb/Sr ratio indicate that this rhyolite is more highly evolved than the tuffs and intrusions.

The three plugs of rhyolite associated with sample 143 cover only several tens of square meters. Tentative correlation of map unit Trsv with the rhyolite of sample 143 does not greatly increase the amount of magma required to generate these units. Continued differentiation of the magma that produced the ash-flow tuffs and monzonites could have produced high silica liquids; extrusion of these magmas could account for the rhyolites.

Present data are not sufficient to resolve the possible differences between the magma that generated the tuffs, intrusions, and rhyolites, and the magma that generated the less silicic rocks. The andesitic magma, if distinct, would have been characterized by higher Sr and lower alkali contents than the other magma. The andesites approach the chemical composition that Robinson (1972) postulated for the parent magma of the Silver Peak center, although the andesites of Stonewall have lower CaO and MgO concentrations, and are slightly enriched in SiO₂ and alkalis. The close comparison suggests that the andesites may have differentiated only slightly from their parent magma.

The limited chemical spectrum of rocks analyzed, in particular the absence of rocks with mafic composition, makes it imperative to consider the presence of multiple magmas within the Stonewall center only a hypothesis. Crystallization and segregation of calcium bearing
phases, and subsequent enrichment of the remaining liquid in silica and alkalis, would allow progression from the composition of the andesites to the composition of the ash-flow tuffs and related intrusions. If such processes were active within the Stonewall magma, only one source is required to explain the generation of igneous rocks on Stonewall.

If only one magma existed, it may have been simultaneously tapped at different levels. This would account for the close chronologic relations (see the following chapter) of units with varying chemistry. Christiansen et al. (1977) postulated a similar process for the eruption of the Ammonia Tanks Member of the Timber Mountain Tuff.

Conclusive evidence for the involvement of more than one magma in the generation of the igneous rocks of Stonewall Mountain must be sought in a program of further chemical analyses.

Regional Comparison of the Stonewall Center

Comparison of Stonewall Mountain with other potassic volcanic centers in the western U.S. shows that although chemically similar (Table 9), on a basis of FeO*/MgO (FeO* = total iron as FeO) versus for rocks of similar silica values, Stonewall rocks are relatively enriched in K₂O (Fig. 22). The analyzed specimen of ash-flow tuff from Stonewall has been devitrified, however, and this may have increased the K₂O content.

Although the general pattern of Late Miocene volcanism in the western Great Basin is apparently one of bimodal basalt-rhyolite associations (Stewart et al., 1977; Christiansen and Lipman, 1972),
Table 9. Comparison of chemical analyses from the Black Mountain, Silver Peak, and Stonewall Mountain volcanic centers, for rocks with similar silica values. Black Mountain data from Noble and Christiansen (1974); Silver Peak data from Robinson (1972); Stonewall Mountain data, this report.

<table>
<thead>
<tr>
<th></th>
<th>Black Mountain</th>
<th>Silver Peak</th>
<th>Stonewall Mountain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
<td>9</td>
<td>06</td>
</tr>
<tr>
<td>SiO₂</td>
<td>63.6</td>
<td>75.3</td>
<td>63.17</td>
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<tr>
<td>TiO₂</td>
<td>0.88</td>
<td>0.11</td>
<td>0.84</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>16.8</td>
<td>12.08</td>
<td>16.49</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.7</td>
<td>0.85</td>
<td>3.13</td>
</tr>
<tr>
<td>FeO</td>
<td>1.7</td>
<td>0.98</td>
<td>1.05</td>
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<tr>
<td>MnO</td>
<td>0.14</td>
<td>0.07</td>
<td>0.10</td>
</tr>
<tr>
<td>MgO</td>
<td>0.87</td>
<td>0.01</td>
<td>1.15</td>
</tr>
<tr>
<td>CaO</td>
<td>2.0</td>
<td>0.33</td>
<td>3.18</td>
</tr>
<tr>
<td>Na₂O</td>
<td>4.9</td>
<td>4.44</td>
<td>4.42</td>
</tr>
<tr>
<td>K₂O</td>
<td>5.0</td>
<td>4.85</td>
<td>4.83</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.33</td>
<td>0.01</td>
<td>0.34</td>
</tr>
<tr>
<td>H₂O⁺</td>
<td>0.72</td>
<td>0.41</td>
<td>0.57</td>
</tr>
<tr>
<td>H₂O⁻</td>
<td>0.50</td>
<td>0.04</td>
<td>0.41</td>
</tr>
</tbody>
</table>
Figure 22. Comparison of FeO*/MgO ratio against amount of K₂O in rocks with similar (63%) silica values. The drawing is adapted from Noble et al. (1976), who plotted the data from the other volcanic centers. BM = Black Mountain, SP = Silver Peak, NWM = northern White Mountains, EV = Eureka Valley Tuff, STO = Stonewall.
a series of potassic volcanic centers has been described by
Noble et al. (1976). Stonewall Mountain is located in the middle
of the array of centers (Fig. 23). The presence of many volcanic
centers suggests that regional processes for generating potassic
magmas must be sought. Noble (1972) summarized the possible
origins for such magmas, saying:

"The diversity of rock types erupted during the latest
Miocene and Pliocene in the southern Great Basin may
reflect the combined effects of a fragmented relict
plate of oceanic lithosphere overlain by a spreading
asthenosphere and fragmenting crust, and the resultant
generation of primary magmas at various depths from not
only the descending plate but also mantle material
originally located at various depths both above and
possibly below the descending plate."

The close similarity of the analyses from Stonewall Mountain
and the analyses from the Black Mountain and Silver Peak volcanic
centers (Table 9) may be interpreted to suggest that magmatic processes
that took place at Stonewall Mountain were similar to processes
that have been documented from these other volcanic centers. Noble
and Christiansen (1974) record Sr\(^{87}/Sr^{86}\) initial ratios of 0.7069 to
0.7076 for trachytes and 0.7071 to 0.7111 for sanidine or anorthoclase
phenocryst separates from ash-flow tuffs within the Black Mountain
volcanic center. The low Sr\(^{87}/Sr^{86}\) ratios suggest that the Black
Mountain rocks had an origin in the mantle. A mantle origin has
also been suggested by Robinson (1972) for rocks in the Silver Peak
volcanic center. Keith (1977) and Robinson (1972) both regarded
Silver Peak rocks as the product of differentiation involving
Figure 23. Location of Stonewall Mountain (SM) and other late Tertiary potassic volcanic centers. M, Markleville; LW, Little Walker; BA, Bodie-Aurora; SP, Silver Peak; BM, Black Mountain; SC, Silent Canyon; PT, Paintbrush-Timber Mountain; KS, Kane Springs Wash.; OV, Ox Valley (from Noble et al., 1976, Figure 1).
fractional crystallization. The depletion of the rocks of Stonewall Mountain in mafic minerals could be a result of fractional crystallization of the magma; whether the magma is a mantle melt, or whether it has been contaminated by crustal material, can not be determined at this time.

Conclusions

Although secondary processes may have been affected the igneous rocks of Stonewall, the data reported here may be interpreted to suggest that the rocks of Stonewall fit a differentiation sequence. Results of analyses of Stonewall rocks differ in detail from results obtained in other Late Miocene volcanic centers in the western United States, but Stonewall fits the regional pattern of volcanic centers with high $K_2O$ and $Na_2O$ values.
CHAPTER 4

POTASSIUM-ARGON DATING

Although the Stonewall Mountain volcanic center has been assumed to be Miocene on the basis of patterns of regional volcanic activity, no isotopic dating of rocks from the volcanic center has been done prior to this study. Estimates by Cornwall (1972) and Ashley (1974), based on field observations, suggested that volcanic activity on Stonewall preceded the 7.5 m.y. old Spearhead Tuff of the Black Mountain volcanic center. Ekren (1968, p. 15) illustrates Stonewall Mountain as older than 11 m.y.; no indication of the basis for this date is given. D.C. Noble (pers. comm., 1974) estimated a date of 13.5 to 15 m.y. b.p. (before present) for activity on Stonewall. Field relations of rock units on Stonewall do not permit more precise estimates of the age of activity, nor do they indicate the span of volcanic and intrusive activity. Therefore, potassium-argon dating of rocks from Stonewall was done, in order to establish the timing of igneous activity, and better relate the volcanic center to regional volcanic patterns. Samples were analysed in the Potassium-Argon laboratory at Ohio State University, under the direction of Dr. John F. Sutter.
Biotite and feldspar mineral concentrates were obtained by a combination of heavy liquid, magnetic and paper shaking techniques. The one whole rock sample was crushed to 45 to 60 mesh, and washed with dilute (10%) HCl.

Potassium analyses were done by single-channel flame photometry, using a Zeiss model PF-5 and absolute K standard solutions prepared from stoichiometric KCl. Sample solutions were prepared by employing the cation separation techniques of Cooper (1963).

Argon was extracted from the samples and purified using techniques described by Dalrymple and Lanphere (1969; p. 62-65). Argon isotopic composition and concentration measurements were made using isotopic dilution techniques (Dalrymple and Lanphere, 1969; p. 54-62) and a Nuclide Corp. Model SGA-6-60 mass spectrometer operated in the static mode. Both bulb and manifold-type $^{38}\text{Ar}$ tracers were used.

Results of the Dating Program

Seven samples have been analyzed; the age data is presented in Table 10 and the sample locations are indicated on Figure 24. Hydrothermal alteration of the rocks, as well as limited occurrences of minerals suitable for dating by the K-Ar method, prevented a more comprehensive dating program.

No petrographic evidence is presented in any of the analyzed samples which would suggest that they have more than a simple cooling history. Field evidence described in Chapter 2 (p. 52, 59) suggests that the monzonites were emplaced at shallow depths. No petrographic evidence for large scale post-emplacement heating of
Table 10. Results of K-Ar analyses.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Map Unit</th>
<th>Mineral</th>
<th>( %K )</th>
<th>Moles ( \frac{40\text{Ar}^*}{\text{gm}} ) (x 10(^{-11}))</th>
<th>( \frac{40\text{Ar}^*}{40\text{K}} ) (x 10(^{-4}))</th>
<th>( 40\text{Ar}_R ) (%)</th>
<th>Apparent Age (m.y.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>89</td>
<td>Tm</td>
<td>Biotite</td>
<td>6.424</td>
<td>9.403</td>
<td>4.904</td>
<td>37.4</td>
<td>8.42( \pm ) .22</td>
</tr>
<tr>
<td>53</td>
<td>Tm</td>
<td>Biotite</td>
<td>6.330</td>
<td>8.951</td>
<td>4.738</td>
<td>42.6</td>
<td>8.14( \pm ) .23</td>
</tr>
<tr>
<td>48</td>
<td>Tad</td>
<td>Whole Rock</td>
<td>3.191</td>
<td>4.215</td>
<td>4.426</td>
<td>64.7</td>
<td>7.60( \pm ) .12</td>
</tr>
<tr>
<td>121</td>
<td>Tms(_1)</td>
<td>Biotite</td>
<td>5.926</td>
<td>7.741</td>
<td>4.377</td>
<td>37.8</td>
<td>7.52( \pm ) .17</td>
</tr>
<tr>
<td>-</td>
<td>Tms(_1)</td>
<td>Feldspar</td>
<td>5.146</td>
<td>6.581</td>
<td>4.285</td>
<td>56.6</td>
<td>7.36( \pm ) .12</td>
</tr>
<tr>
<td>65</td>
<td>Twt</td>
<td>Biotite</td>
<td>6.463</td>
<td>8.406</td>
<td>4.358</td>
<td>48.7</td>
<td>7.48( \pm ) .20</td>
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<tr>
<td>38</td>
<td>Twt</td>
<td>Feldspar</td>
<td>3.603</td>
<td>4.501</td>
<td>4.185</td>
<td>37.8</td>
<td>7.19( \pm ) .54</td>
</tr>
<tr>
<td>143</td>
<td>Trv</td>
<td>Biotite</td>
<td>8.501</td>
<td>7.741</td>
<td>3.051</td>
<td>40.9</td>
<td>5.24( \pm ) .18</td>
</tr>
</tbody>
</table>

\( \lambda = 5.543 \times 10^{-10}\text{yr}^{-1} \)

\( \lambda_e = 0.581 \times 10^{-10}\text{yr}^{-1} \)

\( \lambda_\beta = 4.962 \times 10^{-10}\text{yr}^{-1} \)

\( \lambda_e / \lambda_\beta = 0.1171 \)

\( 40K/K = 1.167 \times 10^{-4} \) moles/mole

\(^1\)\( \%K \) is the average for duplicate analyses; the average percent difference for the analyses is 1.19 percent.
Figure 24. Locations of samples selected for K-Ar analyses.
the intrusions has been found. The shallow cooling of the intrusions, at depths where retention of argon in the minerals would not have been disturbed by the geothermal gradient, suggests that the apparent ages of the intrusive rocks are cooling ages. Although the andesite (sample 48) was emplaced at or near the surface, and the tuffs (samples 38 and 65) are extrusive, these units may have been slightly disturbed, and their apparent ages slightly reset, by emplacement of the monzonites. The rhyolite (sample 143) was also emplaced near the surface; its apparent age is probably a simple cooling age.

Two dates have been obtained on biotite separated from samples of the monzonite along the north side of the mountain (map unit Tm). Biotite from sample 89, which is located in the western portion of the outcrop area, yielded a date of $8.42 \pm 0.22$ m.y., whereas biotite from sample 53, which is near the eastern limit of the monzonite outcrop area, about four kilometers east of sample 89, yielded a date of $8.14 \pm 0.23$ m.y.. Application of the critical value test of Dalrymple and Lanphere (1969, p. 120) demonstrates that the difference between the dates reported from these biotites is too small to be significant, and therefore the results may be interpreted to suggest, although they do not prove, that the samples are the same age.

Although the dates on the monzonite are the oldest dates obtained from the study of Stonewall, it should be noted that andesite (Ta), dacite (Td), rhyolite breccia (Tr1), and the thick sequence of flows and ash-flow tuffs which form most of Stonewall, were extruded from
the vent complex prior to emplacement of the monzonite. It has not been possible to concentrate enough suitable material from these older rocks, and therefore they have not been dated.

The critical value test indicates that the difference in dates between the monzonite and the next younger unit, the andesite dike (sample 48, map unit Tad) is significant at the 95% confidence level. The difference is slight, however, and may not be confirmed by further dating of these two units. The $7.60 \pm 0.12$ m.y. date on the andesite is statistically indistinguishable from dates of $7.48 \pm 0.20$ m.y. on biotite separated from an air-fall tuff that crops out adjacent to the eastern phase of the anorthoclase-bearing monzonite (sample 65, map unit Twt), and a date of $7.19 \pm 0.54$ m.y. on a feldspar concentrate from an ash-flow tuff unit that crops out east of the main part of the mountain (sample 38, map unit Twt). This tuff has tenatively been correlated with the thick ash-flow tuff sequence that caps the mountain. Thin section examination of the ash flow tuff shows alteration of some of the feldspars. This alteration might have led to a loss of argon, and therefore an anomalously young date for a unit that is intruded elsewhere on the mountain by monzonite which yields a date of 8.4 m.y.

Biotite and feldspar concentrates from the anorthoclase-bearing monzonite (sample 121, map unit Tms1) have yielded dates of $7.52 \pm 0.17$ m.y. and $7.36 \pm 0.12$ m.y. respectively. The difference between these dates is too small to allow them to be distinguished, and
therefore the dates probably represent a single cooling event. Application of the critical value test shows that the dates on the anorthoclase-bearing monzonite can not be separated from the dates on the andesite (sample 48), the ash-flow tuff (sample 38), and the air-fall tuff (sample 65).

Biotite separated from the vitrophyric margin of a small rhyolite neck (sample 143, map unit Trv) yields a date of $5.24 \pm 0.18$ m.y., which is statistically distinct from the other dates obtained on Stonewall. Field relations suggest that this rhyolite is the youngest unit on the mountain; the dating also suggests this is the case.

Interpretation of the Results

The close agreement of dates within individual rock units, and the limited range of dates between rock units, suggests that the dates reported are geologically meaningful, and generally depict the chronologic development of the mountain.

The results suggest, but do not prove, that the igneous history of Stonewall Mountain can be divided into three phases:

1. The first phase included eruption of andesite, rhyolite, and the voluminous ash-flow tuffs, followed by emplacement of the monzonite along the north side of the mountain about 8.1 to 8.4 m.y. b.p.

2. The second phase, which was probably active from around 7.6 to 7.2 m.y. b.p., was dominated by intrusion of the anorthoclase-bearing monzonite, and extrusion of related tuffs. Some andesitic volcanism was also probably included.
3. The third phase was marked by the emplacement, after an apparent period of quiescence, of several small rhyolite necks.

Further dating might refine this interpretation of the geochronology of Stonewall Mountain. Similar volcanic centers in western Nevada (Robinson, 1972; Christiansen et al., 1976) typically had a shorter duration of activity than the approximately 9 m.y. to 5 m.y. span for Stonewall; this suggests that further dating might not yield results which would extend the known duration of activity on Stonewall.

Regional Implications

At the same time that Stonewall was active, several other volcanic centers along the Walker Lane and in other parts of western Nevada were also active. The Silver Peak volcanic center (see Fig. 25) was active from 6 to 4.8 m.y. b.p. (Robinson, 1972); these dates overlap with the youngest activity on Stonewall. The Black Mountain volcanic center (Fig. 25) was active from about 7.5 to 6.2 m.y. b.p. (Noble and Christiansen, 1974); which overlaps with the date for the anorthoclase-bearing monzonite and related units on Stonewall. Several other volcanic areas, including the Bodie center (9-5 m.y. b.p.) and the Shoshone volcanics in Death Valley (8-6 m.y. b.p.) were active at the same time as Stonewall. Stewart et al. (1977) outlined an area characterized by volcanic activity between 17 and 6 m.y. b.p.; Stonewall is in the middle of this area.
Figure 25. Selected Tertiary Volcanic Centers and the Walker Lane - centers "dominantly" older than 10 m.y. + centers "dominantly" younger than 10 m.y. V = Virginia City, M = Markleville, LW = Little Walker, B-A = Bodie - Aurora, T = Tenopah, SP = Silver Peak, G = Goldfield, SM = Stonewall Mountain, MH = Mount Helen, BM = Black Mountain, TM = Timber Mountain (after Ekren et al., 1971, Noble et al., 1976, Stewart et al., 1977).
CHAPTER 5

HISTORICAL DEVELOPMENT OF THE STONEWALL
MOUNTAIN VOLCANIC CENTER

Regional Geologic Setting

Pre-Tertiary rocks on and in the vicinity of Stonewall include Precambrian and Paleozoic sedimentary rocks and isolated Mesozoic intrusions. The Precambrian and Paleozoic rocks record a complex history of deposition, folding, faulting, and low grade regional metamorphism. Some of these events are recorded in the pre-Tertiary rocks exposed on Stonewall; the sedimentary units have been folded into a plunging syncline, faulting which locally repeats the section, and the siltstones have been slightly metamorphosed. Evidence for probably Paleozoic uplift in the vicinity of Stonewall is provided by the outcrop of quartzite conglomerate.

Although no record of the Mesozoic is preserved on Stonewall, Jurassic quartz monzonite is exposed in the vicinity of the Goldfield mining district (Ashley, 1974), and a small outcrop of Mesozoic (?) leucogranite has been mapped by Ekren et al. (1971) in the Cactus Range.

Prior to the inception of volcanic activity on Stonewall, the Tertiary geologic development of the area was marked by extensive
volcanism and faulting. Other volcanic centers in the area predate Stonewall: mineralization of rocks at Goldfield took place about 21 m.y. ago (Silberman and Ashley, 1970), volcanic units in the Cactus Range yield ages of 28 to 16 m.y. (Marvin et al., 1970, 1973), and many of the volcanic units of the southwestern Nevada volcanic field yield dates between 16 m.y. and 9.5 m.y. ago. With the possible exception of the Ranier Mesa and Ammonia Tanks Members of the Timber Mountain Tuff, none of these older volcanic units are likely to have reached the area of Stonewall.

Potassic volcanic centers which may be related to Stonewall were deliniated in the discussion of chemistry (Fig. 11); several of these centers were active at the same time as Stonewall.

Although Tertiary faulting probably began in western Nevada about 26 m.y. ago, formation of Basin-Range type faults probably did not begin until about 17 m.y. ago (Ekren et al., 1968, Noble, 1972). The area of Stonewall was probably one of low relief until about 11 m.y. ago. Between 11 and 7 m.y. ago, however, high angle faulting created ranges and valleys which generally follow present topographic features (Ekren et al., 1968); the valley north of Stonewall may have been a low area about 7 m.y. ago (Ashley, pers. comm., 1976).

The faults which bound Stonewall on its north and west sides are related to the regional fault patterns, and are likely to have existed prior to the inception of igneous activity on Stonewall.
At the inception of volcanism, the terrain at Stonewall was one of complexly folded and faulted Precambrian and Paleozoic strata, that had been intruded by Mesozoic granites, partially covered by Tertiary volcanic units, and displaced by high angle faults into Basin-Range topography similar to that which exists today.

Geological Development of the Stonewall Mountain Volcanic Center

The presence of the Walker Lane as a zone of crustal weakness, and extension related to development of geologic structures in the Basin and Range, may have led to the development of fractures in the crust along which the Stonewall Mountain magma(s) rose.

Volcanic and intrusive rocks of Stonewall may be the product of tapping a differentiated magma chamber at different levels to generate the chemical range and overall petrographic similarity found in these rocks. Alternatively, they may be the product of two spatially and chronologically related magmas of slightly different chemistry.

Volcanic activity on Stonewall began with the extrusion of andesite (Ta) and dacite (Td), and the emplacement of a thick sequence of rhyolite flows and breccias (Tr₁). The andesite occurs as isolated outcrops, and is overlain by rhyolite characterized by many breccia zones. Some of these breccia zones, especially near the valley south of Stonewall Spring, may represent vent areas for the rhyolite. Argillic and local propylitic alteration occurred after the emplacement of the rhyolite.
The oldest ash-flow tuff unit was emplaced after the rhyolite breccias. This trachytic tuff (Ttt) is found in the northern and western parts of the mountain. It is locally in contact with a rhyolite flow sequence (Trb), which in turn is overlain by phenocryst- and lithic-rich ash-flow tuffs (Tpl).

Collapse, as a result of withdrawal of magma from the underlying chamber, occurred after emplacement of the trachytic tuffs and rhyolite flows and breccias. This collapse took place while the tuff was still warm enough to be plastically deformed.

The eastern-most exposure of the phenocryst- and lithic-rich tuff (Tpl) is intercalated with the thick red lithic tuff (Trlt) that forms most of the high ridges of Stonewall. This ash-flow tuff was extruded over a terrain created by the earlier units, and may have been extruded while the underlying units still retained some of their heat.

After the second episode of collapse, about 8.3 m.y. b.p., monzonite (Tm) was intruded at shallow depths along the north side of the mountain. Quartz and carbonate veins, and minor amounts of gold and silver, are associated with the monzonite.

The monzonite was followed by andesite, air-fall tuffs, and anorthoclase-bearing monzonite and syenite, which were emplaced about 7.6 to 7.3 m.y. b.p..

The andesite (Tad) occurs as a dike or sill, emplaced through Precambrian sediments, the oldest ash-flow tuff, the phenocryst- and
lithic-rich tuff, and apparently, on the basis of K-Ar dates, the monzonite.

Eruption of air-fall tuffs (Tat) was probably associated with the first stages of emplacement of the anorthoclase-bearing intrusions. Several laharian breccias, composed of fragments of the ash-flow tuff which caps the mountain, are intercalated with the lower parts of the air-fall tuffs.

The anorthoclase-bearing units (Tms₁₋₄) are a sequence of multiple intrusions; the more silicic rocks dominate in the central and southwestern parts of the mountain, and they have been intruded by a less silicic, but anorthoclase-bearing, monzonite in the southeastern part of Stonewall.

The anorthoclase-bearing intrusions, like the older monzonite along the northern part of the mountain, were probably emplaced at shallow depths. Outcrop patterns strongly suggest that magma emplacement was localized by northwest and northeast trending fracture zones. The younger monzonites do not have the veins and mineralization characteristic of the older intrusion.

Overlying the air-fall tuffs, and in underlain stratigraphic relation to volcanic units on Stonewall, are a series of rhyolite flows and domes (Trf₁,₂), as well as small outcrops of vitrophyre (Tv), ash-flow tuff (Tbm), and basalt (Tb). The rhyolite flows and domes are found only in the area east of Stonewall. They have been cut by high-angle faults.
Outcrops of rhyolite flows (Tr2) that are petrographically distinct from the flows and domes which overlie the air-fall tuff occur near the southeast corner of the mountain. These rhyolites are apparently younger than the red lithic tuff that caps the mountain.

Volcanic activity on Stonewall ceased after the emplacement of a series of rhyolite necks (Trv, Trsv) that crop out in the north-eastern and central parts of the mountain. These rhyolites were intruded about 5.2 m.y. b.p., after an apparent hiatus of several million years in igneous activity on Stonewall.

Although existing topographic features on Stonewall can not be related to features in typical calderas or cauldrons, the steep dips and annular distribution of strikes of eutaxitic structures in the ash-flow tuffs, the apparent confinement of most of these tuffs to areas within the mountain, and the location of intrusive rocks as a nearly complete ring round the mountain, suggest that Stonewall is a volcanic center that at one time had a central depression and an outer, circular fracture zone. The relatively large amount of intrusive rock exposed on Stonewall may be a result of either deeper erosion than many other volcanic centers of similar age, or emplacement of the intrusions at a higher level which would allow the intrusions to be exposed sooner on Stonewall Mountain than in other centers.
Post-volcanic Development

Although volcanic activity ceased about 5 m.y. b.p., tectonic activity on Stonewall continues with Basin-Range faulting along the north and west margins of the mountain (Figure 26). An earthquake north of Stonewall (Slemmons et al., 1964), multiple fault scarps preserved in alluvium, and truncated spurs on ridges along the north edge of the mountain are indications of continuing tectonism. Exposure of intrusive rocks (Tm) and quartz veins along the scarps at the north edge of the mountain suggests that at least 300 m. of uplift, and probably much more, has taken place along these faults. This uplift may account for much of the present topographic relief of Stonewall Mountain.
Figure 26. Scarp developed by Basin and Range type faulting along the west side of Stonewall.
APPENDIX A

PLATE 1

Preliminary Geologic Map of the Stonewall Mountain Volcanic Center, Nye County, Nevada

EXPLANATION

\[ Qa \]
Alluvium, deposits of intermittent streams

\[ Qa, Qoa, Qt, Qls \]
Qa, undifferentiated alluvium
Qoa, older alluvium and colluvium
Qls, landslide deposits
Qt, talus

UNCONFORMITY

\[ Trv \]
Rhyolite vitrophyre, small necks confined to northeastern corner of mountain

\[ Trsv \]
Rhyolite neck, with vitrophyric border; inclusions of red lithic tuff and anorthoclase-bearing monzonite

\[ Tr2 \]
Rhyolite, flows and domes, with breccias and vitrophyres
Miocene

Tbm
Ash-flow tuff, overlying basalt, restricted to area of air-fall tuffs, southeastern corner of map area

Tv
Vitrophyre, crops out only in area of air-fall tuffs, southeastern corner of map area

Tb
Basalt, flows overlying air-fall tuffs, in uncertain stratigraphic relation with rhyolite flows and domes

Trf₁, Trf₂
Rhyolite, thick sequence of flows and domes which crop out overlying air-fall tuff in eastern and northeastern parts of map area, Trf₁ contains biotite

Tat
Air-fall and water-worked tuff bedded, with channels, laharic breccias of fragments of red lithic tuff

Tad
Andesite, massive dike or sill, with inclusion of rhyolite (?)

Tbs
Latite breccia, angular blocks of flow banded latite, to 3 by 10 m., in latite matrix

Trht
Rhyolitic tuff, crops out beneath extrusive flows associated with anorthoclase-bearing monzonite
Miocene

Tms₄
Anorthoclase-bearing monzonite, southern outcrops are intrusive, northern outcrops are extrusive

Tms₃
Syenite, intruded through ash-flow tuff sequence in western part of map area

Tms₂
Anorthoclase-bearing monzonite, finer grained and darker colored than Tms₁

Tms₁
Anorthoclase-bearing monzonite, light-colored, intrudes ash-flow tuff sequence in central and southern parts of mountain

Tm
Monzonite, coarse grained, with finer border phases, associated with quartz and carbonate veins, minor gold and silver

Trlt⁻u
Red lithic ash-flow tuff, rounded inclusions of pre-Tertiary rocks and Tertiary volcanic units, in dark red, aphanitic groundmass. Crystallized tuff, with rare vitrophyres. Eutaxitic structures dip steeply, tuff is highly faulted u, unwelded zones

Tts<⁻ss
Ash-flow tuff and lava flows ss, intercalated volcaniclastic sandstones
Ash-flow tuff, overlying bedded tuff, with several outcrops of unwelded tuff at its top

Rhyolite, flow banded, with intercalated volcaniclastic sedimentary units, crops out adjacent to andesite dike or sill

Ash-flow tuff, phenocryst (sanidine) and lithic (pre-Tertiary rocks and Tertiary volcanic units) rich, propylitic alteration along joints

Rhyolite, flows and breccias, with inclusions of trachytic tuff, rare specular hematite

Trachytic tuff, crystallized, eutaxitic structures dip steeply, extensive faulting, minor folding

Rhyolite, flows and breccias, argillic and propylitic alteration

Dacite, with 5 mm phenocrysts of orthoclase and quartz in an aphanitic, dark-purple groundmass
Miocene

Ta
Andesite, flows and breccias, in part overlain by rhyolite

UNCONFORMITY

Me
Eleana Formation, quartzite conglomerate

Ce
Emigrant Formation, interbedded limestone and chert

Pcr
Reed Formation, massive dolomite, with rare quartzite

Pcw
Wyman Formation, interbedded siltstone and carbonates

Tertiary

Precambrian

Eleana Formation, quartzite conglomerate

Emigrant Formation, interbedded limestone and chert

Reed Formation, massive dolomite, with rare quartzite

Wyman Formation, interbedded siltstone and carbonates
In some cases, contacts have been adjusted to conform with the topography shown on the map.

The base map was compiled at 1:24,000 scale from the following U.S. Geological Survey Quadrangles:

- Goldfield (1:62,500)
- Cactus Spring (1:62,500)
- Scottys Junction NE (1:24,000)
- Tolicha Peak (1:62,500)
MAGNETIC DECLINATION 1968

For explanation of map units, see Appendix I
PRELIMINARY GEOLOGIC MAP

MOUNTAIN VOLCANIC CENTER

BY DUNCAN FOR...

PLATE
ARY GEOLOGIC MAP OF THE STONEWALL VOLCANIC CENTER, NYE COUNTY, NEVADA

BY DUNCAN FOLEY 1978

PLATE 1
SCALE 1:24,000

contour interval 40 feet
APPENDIX B
PLATE 2
CROSS-SECTIONS

Explanation

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
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<tr>
<td>Qls</td>
<td>landslide</td>
</tr>
<tr>
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<td>rhyolite</td>
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f - faults
v - veins
o - vitrophyre
a - locations

where patterns depict attitudes
LIST OF REFERENCES


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